FEARS STRUCTURAL ENGINEERING LABORATORY

RIGID FRAME STUDIES
Final Report
FULL SCALE FRAME TESTS

by

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CHAPTER I

INTRODUCTION

A series of tests was conducted in the Fears Structural Engineering Laboratory, School of Civil Engineering and Environmental Science, University of Oklahoma, using standard rigid frames produced by Star Manufacturing Company, Oklahoma City, Oklahoma. The purpose of these tests was the determination of the structural strength and stiffness of rigid frames. A total of four sets of two standard frames were tested. These frames have been assigned the following designations by Star Manufacturing Company: Frames 1 and 2 are designated as SRLO4 50 20/25 16/25; Frames 3 and 4 are designated as SR4 60 40/25 20/20; Frames 5 and 6 are designated as STR 60 12/25 10/25; and Frames 7 and 8 are designated as STR4 50 12/25 14/25. Reference is made herein as SRLO4 50, SR4 60, STR 60, and STR4 50, respectively. The frames are normally used in pre-engineered buildings with the following design parameters:

	SRLO4 50	SR4 60	STR 60	STR4 50
Clear Span, ft.	50	60	60	50
Design Live Load, psf	20	40	12	12
Design Wind Load, psf	25	25	15	25
Eave Height, ft.	16	20	10	14
Frame Spacing, ft.	25	20	25	25
Roof Slope	1:12	½:12	½:12	½:12

The SRLO4 and SR4 series consist of clear span rigid frames with non-prismatic columns and rafters of shop-welded steel plate. The STR series consists of prismatic columns and either prismatic or non-prismatic rafters. The STR 60 frames had prismatic rafters while the STR4 50 frames had non-prismatic rafters.

The test specimens were fabricated as part of standard production runs. The test set-up and testing procedures were developed using details and descriptions found in the literature. All test set-ups consisted of two frames spaced 24 ft. 0 in. apart, with connecting simple span purlins and girts, standard flange brace angles, and rod braces as shown in Figure 1. However, girts wer not used for frames 5 & 6. Simulated live load was applied using gravity load simulators similar to those described in Reference 1. Load was applied using A-frames and hydraulic cylinders. The A-frames were located inside the test frames for the SR4 60 tests and outside the test frames for the STR4 50 tests.

The purpose of the testing was threefold: 1) to verify existing design procedures used by Star Manufacturing Company to predict deflections and strength, 2) to verify design procedures which were published by Lee when testing was near completion (Reference 2), and 3) to determine bracing requirements for tapered steel members. This report summarizes the testing procedures, instrumentation, and results. Detailed description of the various tests is found in References 3 to 6. Comparison of results is made with the standard Star Manufacturing Company design procedures and with Lee's proposed methods.

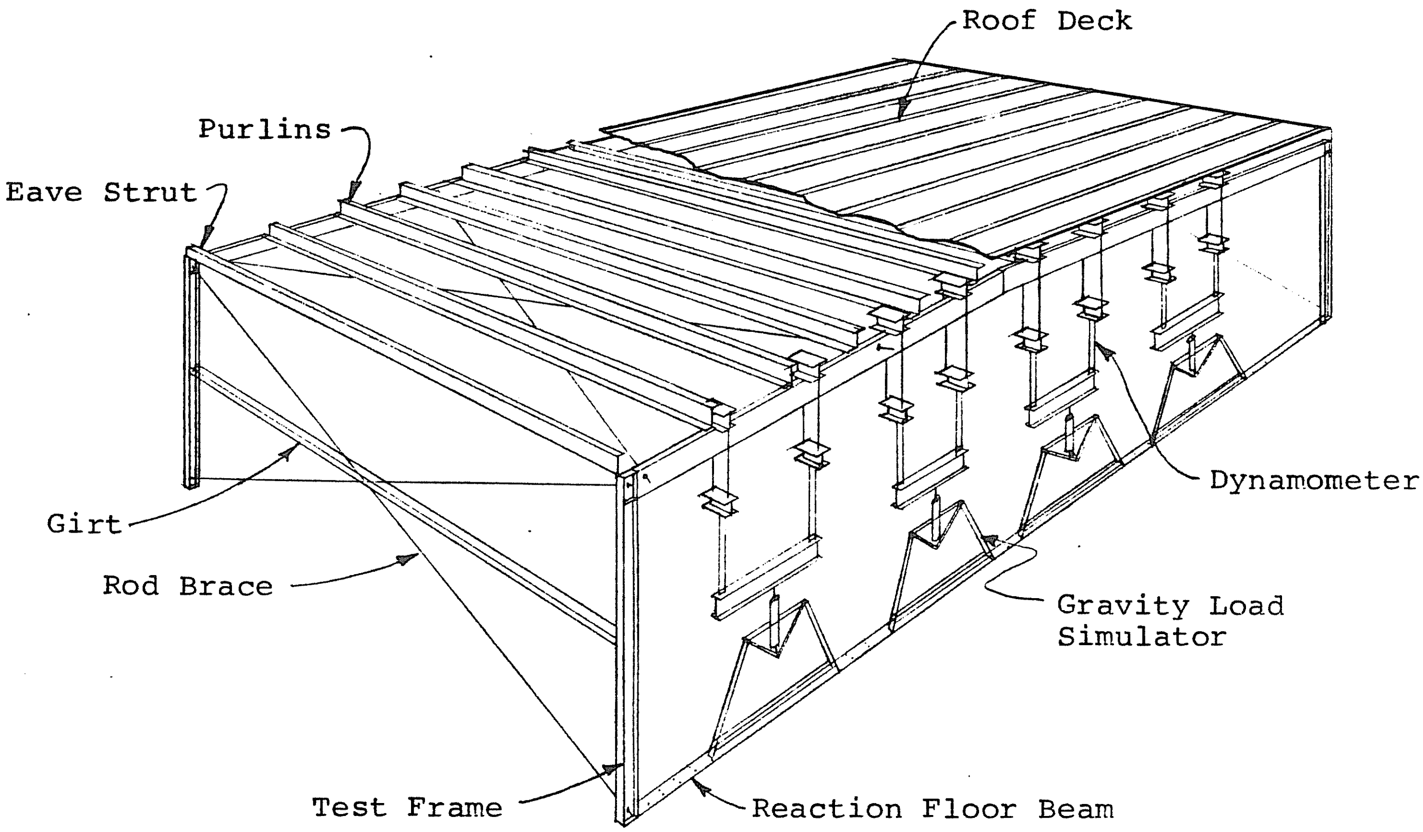


Figure 1. Overall View of Test Set-up

CHAPTER II

TEST DETAILS

2.1 Description of Specimens

Details and dimensions of the test specimens are given in Appendix A. The specimens were fabricated from A572 Gr 50 Steel. The only modification made to the specimens compared to standard production frames was the addition of holes in the top flanges of the rafters to permit installation of loading devices.

2.2 Test Set-up

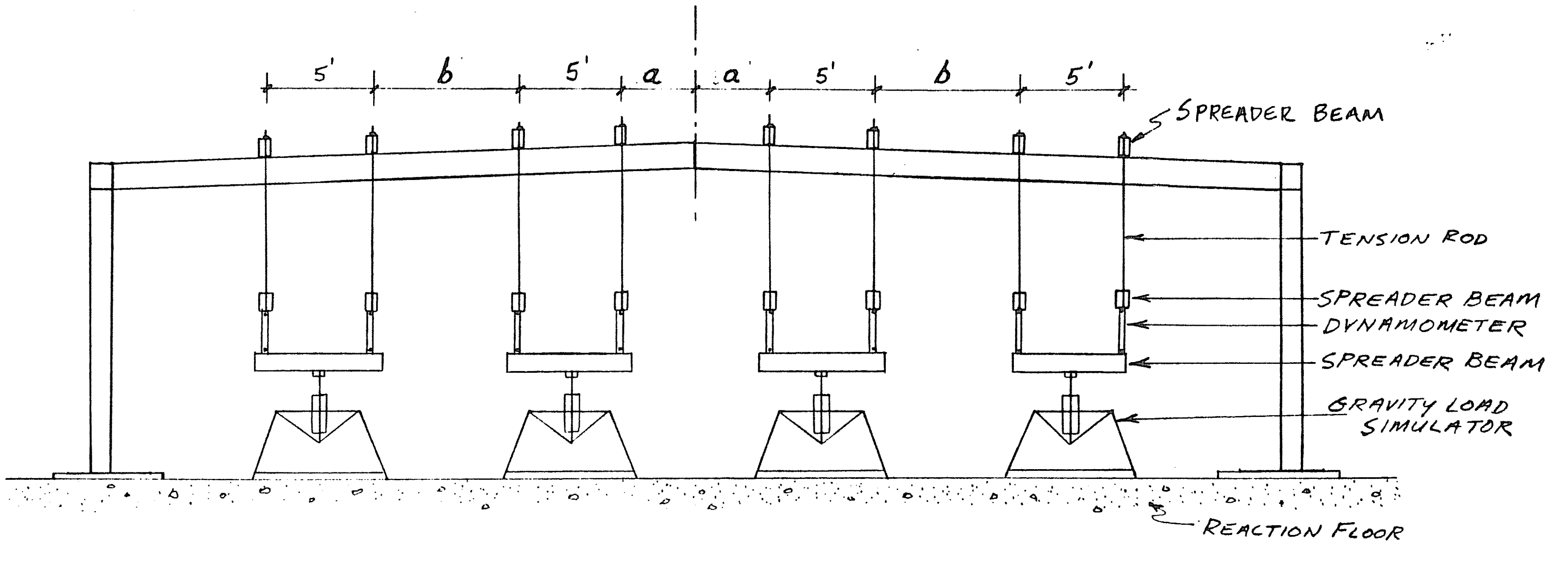
The frames were erected inside the Fears Structural Engineering Laboratory on the laboratory reaction floor. The floor is a concrete slad 30 ft. by 60 ft. by 3 ft. 6 in. deep with four W36 x 150 steel beams embedded in concrete. The slab weighs one million pounds and is capable of reacting 320,000 lb. in any one location. The frames were erected directly over two of the embedded W36 beams, spaced 24 ft. 0 in. apart. Purlins and girts at standard bracing spacings were connected between the frames along with standard rod bracing in both the roof and side walls. However, all the frames except the last series tested (STR4 50) did not have a girt at the standard location of 7 ft. 3½ in. above the column base. Compression flange braces at the standard locations were connected between the purlins and the bottom flanges of the rafters or inside flanges of the columns.

These braces were later moved to nonstandard locations for additional tests to evaluate the lateral buckling strength of rafters. Sheeting was installed on Frames 3 and 4 on the end walls from the eave strut to the girt. The entire roof area was sheeted using standard roof deck and fasteners.

The column base plates were bolted to channel sections which in turn were bolted to the reaction floor beams. Standard A325 bolts with diameters specified by Star Manufacturing Company were used at the rafter to column connections and the peak splice connections. Standard 1/2 in. diameter by 1 1/4 in. hex screws were used to connect all cold-formed parts to the frames. The erection procedures were as near as possible to standard practice and no specific procedure was used to tighten the bolts in the end plate connections.

2.3 Load Applications

Simulated live load was applied using the loading apparatus shown in Figure 2. The loading apparatus consists of a gravity load simulator (Figure 3), a 35 kip tension-compression hydraulic cylinder, spreader beam, two calibrated dynamometers, and spreader beams and tension rods attached to the frame. The simulator is a device which permits horizontal movement of the point of load application while maintaining a vertical line of action of the applied load. For the simulator used in these tests, the point of application of the load can move left or right a maximum of 10 in. and the hydraulic ram will remain vertical.



Frame tested	a, ft.	b, ft.
SRLO4 50	2.5	5.0
SR4 60	3.5	7.0
STR 60	3.5	7.0
STR4 50	2.5	5.0

Figure 2. Simulated Live Load Loading

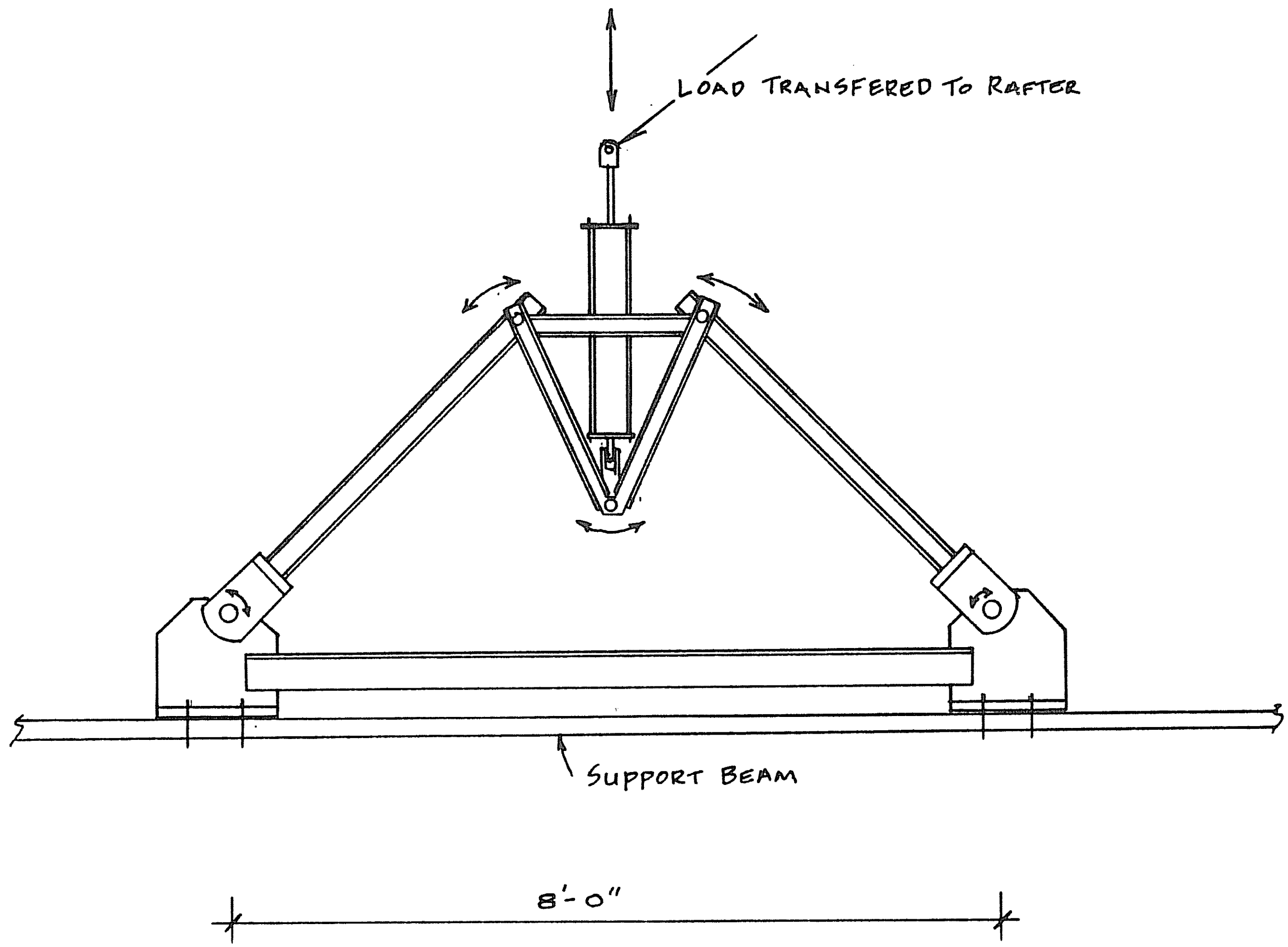


Figure 3. Gravity Load Simulator

Lateral load was applied using an A-frame constructed either adjacent to or inside the frames with hydraulic cylinders and calibrated load cells positioned as shown in Figure 4. For all lateral load applications, load was applied to both frames simultaneously using two identical hydraulic cylinders connected in series to a manual pump.

Five loading schemes were used as shown in Figure 5. Figure 5(a) is the case of unbalanced live load. For this loading, both frames were loaded simultaneously with the four hydraulic rams connected in series to an electric pump. Figure 5(b) is lateral load only, applied as described above. Figure 5(c) shows combined lateral load and unbalanced live load on the windward side. Figure 5(d) shows combined lateral load and unbalanced live load on the leeward side. Figure 5(e) shows full gravity load applied to one frame. For this loading condition, all four hydraulic cylinders were connected in series to an electric pump.

2.4 Instrumentation

Instrumentation consisted of calibrated dynamometers, calibrated load cells, strain gages, dial gages and horizontal deflection gages. Gravity load was measured using the calibrated dynamometers positioned as shown in Figure 2; lateral load was measured using the calibrated load cells positioned as shown in Figure 4.

Vertical deflection of the center line of the frames

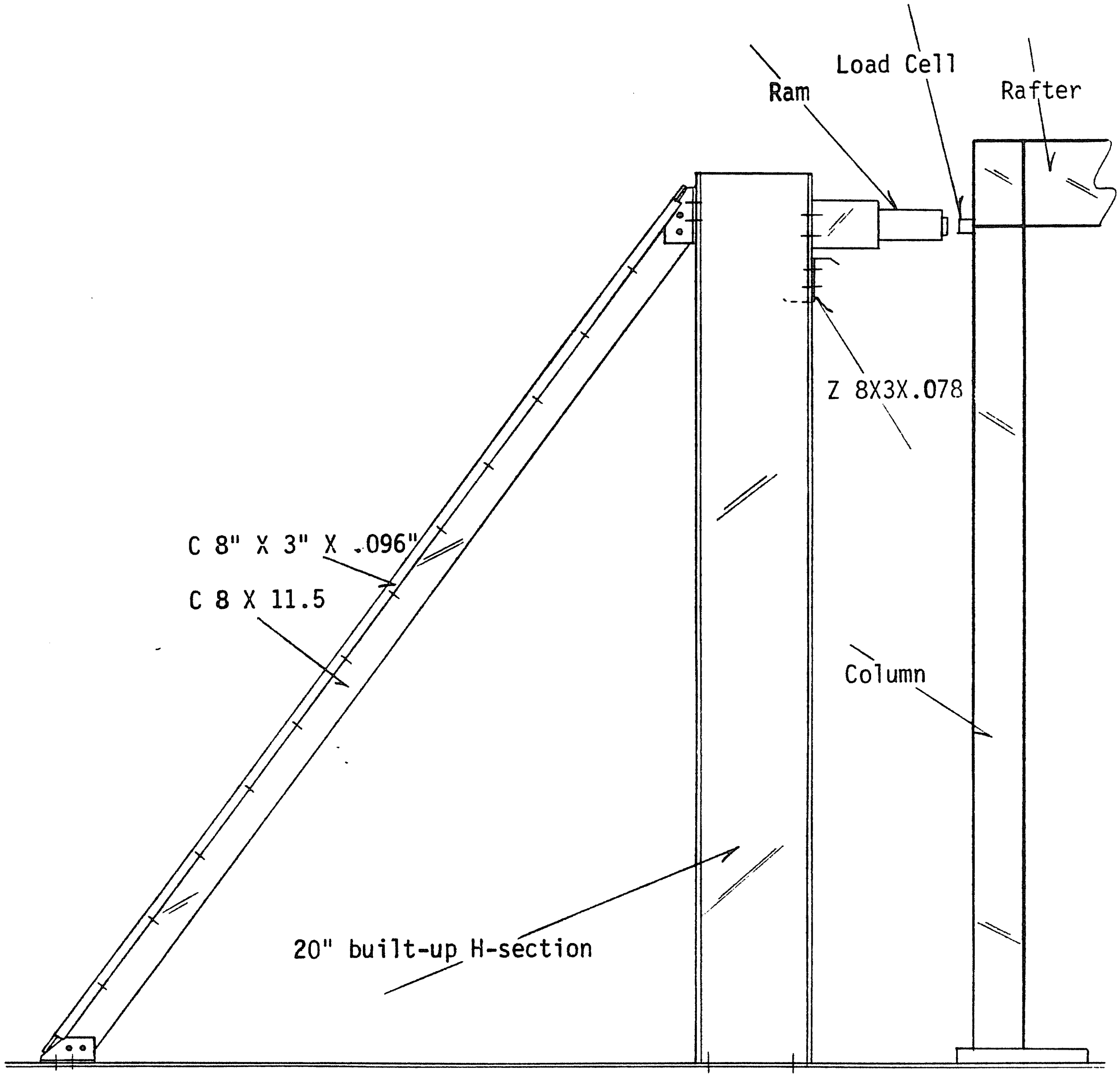
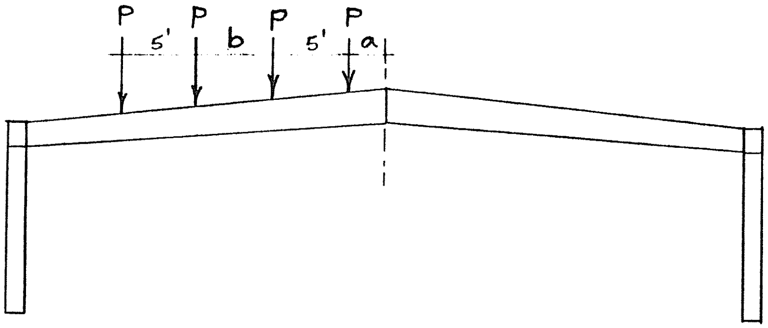
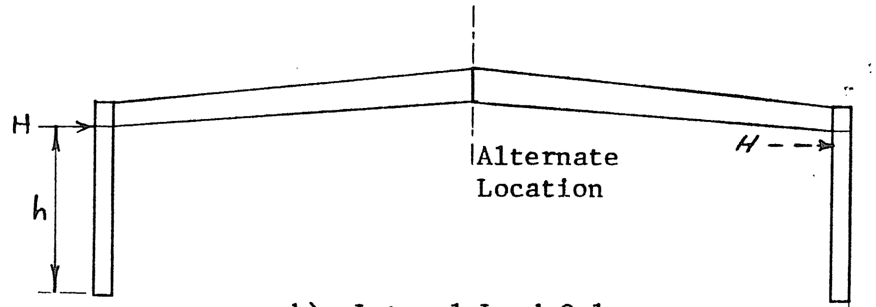


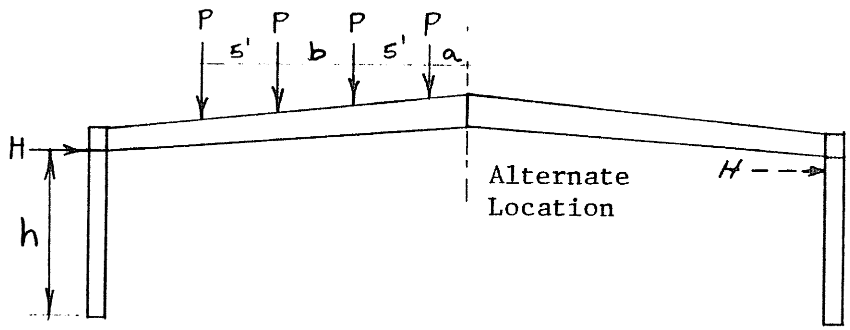
Figure 4. Lateral Load Application



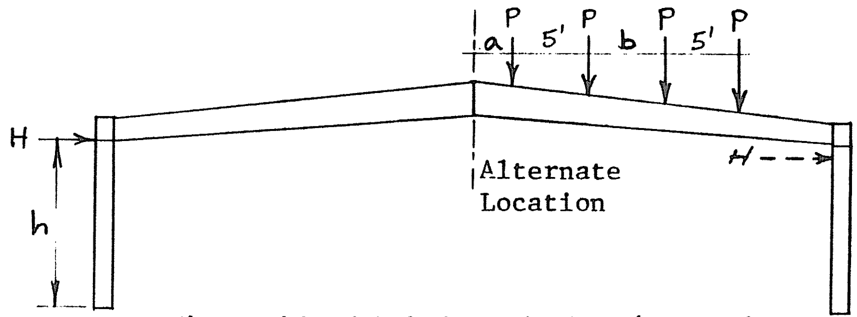
a) Unbalanced Live Load



b) Lateral Load Only

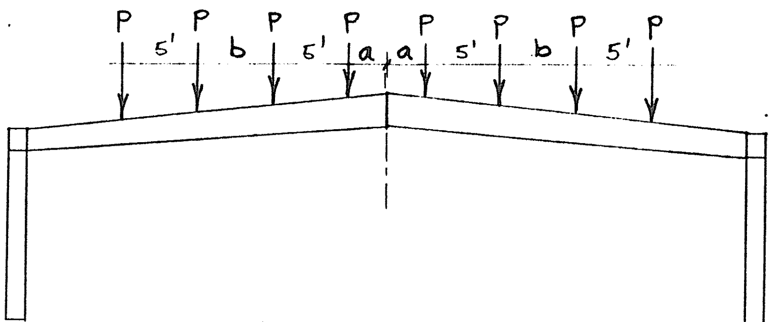


c) Combined Unbalanced Live (windward side) and Lateral Load



d) Combined Unbalanced Live (Leeward side) and Lateral Load

Frame	a,ft.	b,ft.	h,ft.
SRLO4 50	2.5	5	-
SR4 60	3.5	7	16.5
STR 60	3.5	7	-
STR4 50	2.5	5	14



e) Full Live Load

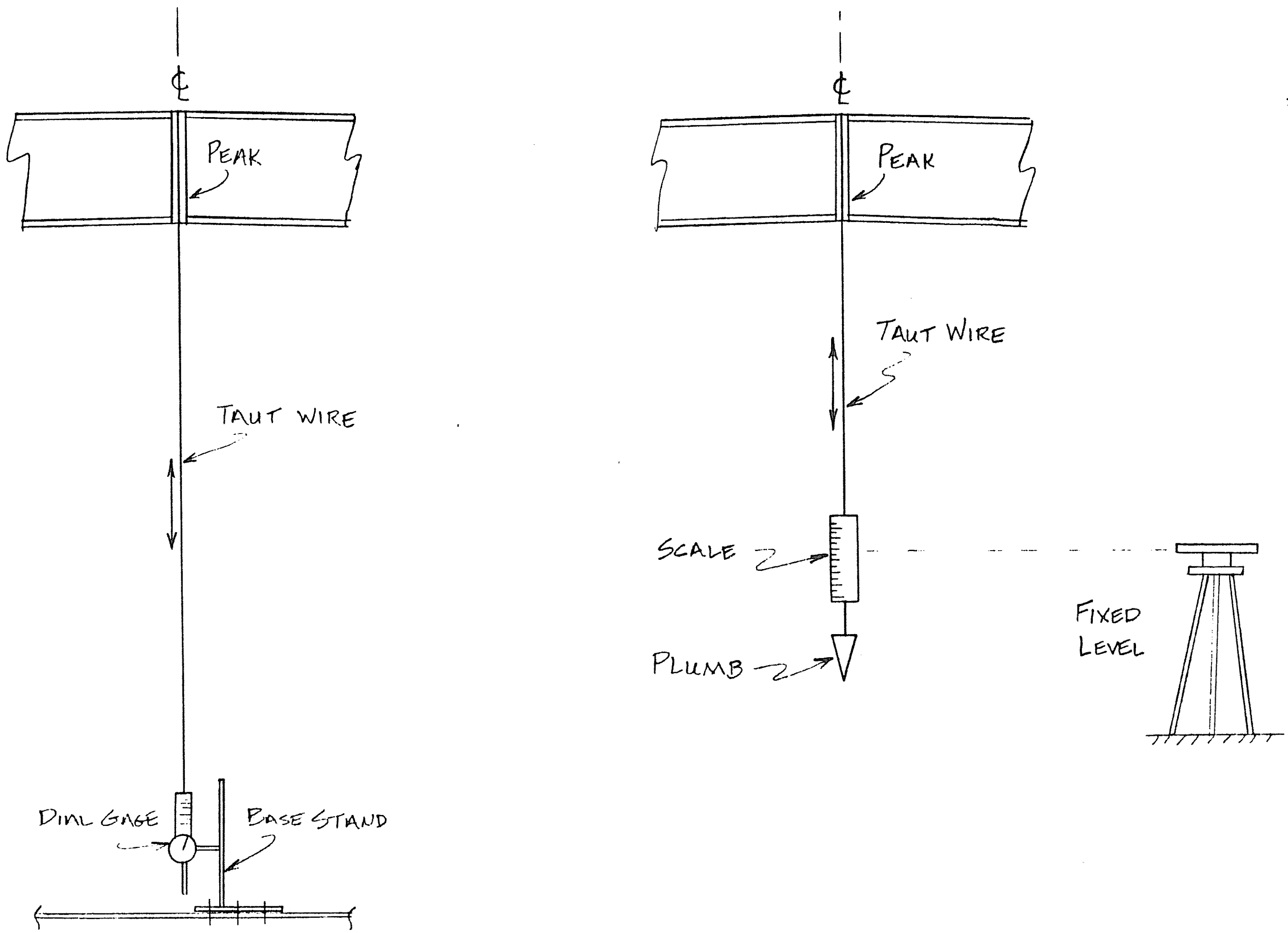
Figure 5. Loading Conditions

was measured using either a taut wire and a dial gage, Figure 6(a), or a weighted scale and a fixed level, Figure 6(b). The former was used for symmetrical loading conditions and the latter for loading conditions where significant frame sidesway was expected. Sidesway of the top of the column was measured using a horizontal scale (0.1 in.) located as shown in Figure 7 and a fixed transit. Lateral movement of the column and rafter flanges was measured by means of a transit set in a fixed position with the telescope free to move only in a vertical plane. Graduated scales (0.1 in.) were attached perpendicular to the plane of the web at the flange locations shown in Figure 8.

Foil strain gages were positioned on all frames at critical locations, as shown in Figure 9. Gages on the same side of the web but on opposite sides of a flange were wired so that the average strain at a particular location was recorded. An electronic data acquisition system was used to record all strain gage data.

2.5 Testing Procedures

Prior to any actual testing, an overall check of the testing apparatus and instrumentation was made and zero readings were recorded. In general, load was applied in increments until near the failure load at which time the increment was decreased. After each load increment, deflection and strain gage readings were recorded and the specimens were



(a) (b)

Figure 6. Measurement of Vertical Deflections

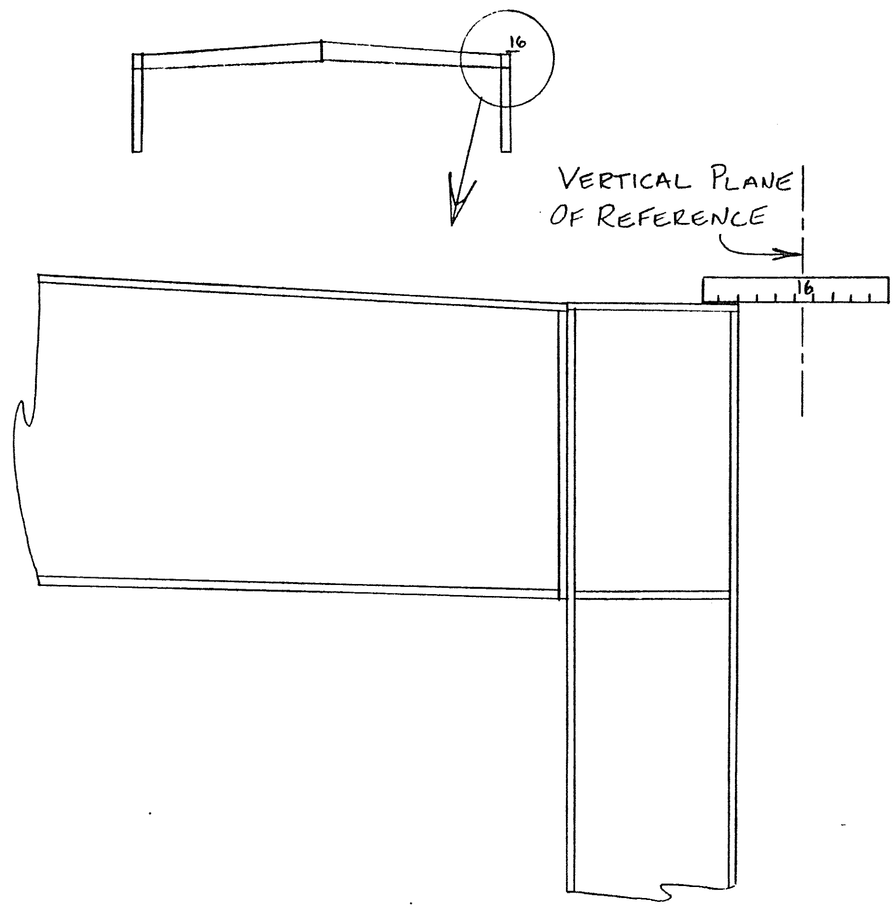


Figure 7. Measurement of Sidesway Deflections

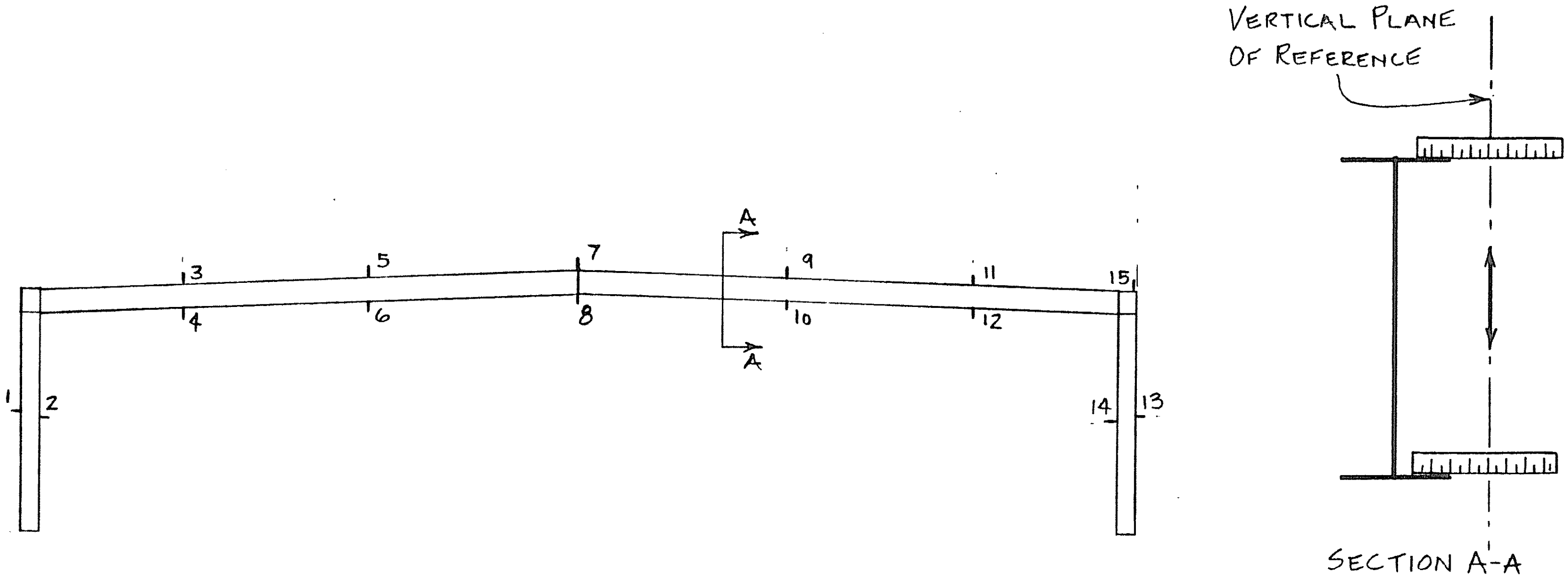


Figure 8. Measurement of Lateral Deflections

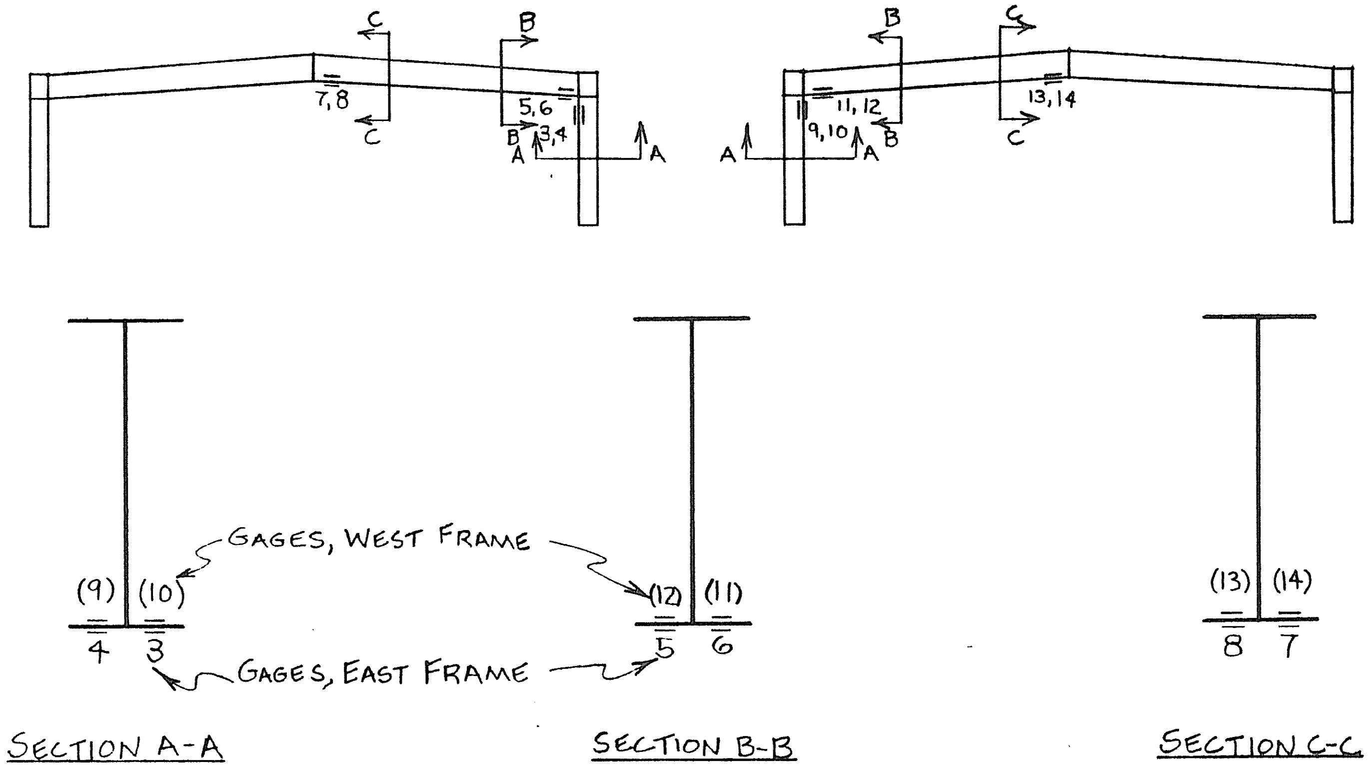


Figure 9. Typical Strain Gage Locations

checked for signs of yielding. Yielding was detected by flaking of mill scale under the whitewash coat on the frames. When the specimens were no longer able to resist any additional loading or had reached the maximum desired load, final readings were taken and the load then removed.

Two types of tests were conducted: tests to verify the performance of the frames relative to analytical predictions for a number of loading cases and tests to determine the load-carrying capacity of the frames under non-standard flange bracing. A summary of the tests performed on the eight frames is given in Table 1.

Table 1

Tests Performed

Frame Type	Frame No.	Case I Full Live Load		Case II Lateral Load		Case III Unbalanced Live Load		Case IV ULL1 + Lat. Load		Case V ULL2 + Lat. Load	
		Std.	Non Std.	Std.	Non Std.	Std.	Non Std.	Std.	Non Std.	Std.	Non Std.
SRL04 50	1	X									
	2	X									
SR4 60	3		X	X		X		X			
	4	X		X		X		X			
STR 60	5	X									
	6	X	X								
STR4 50	7		X	X		X		X		X	X
	8	X		X		X		X		X	X

Notes:

Std. - denotes standard flange brace spacings
Non Std. - denotes non standard flange brace spacings
ULL1 - denotes unbalanced live load on windward side
ULL2 - denotes unbalanced live load on leeward side.

CHAPTER III

ANALYTICAL PROCEDURES

3.1 Introduction

In this chapter, the analytical procedures currently used by Star Manufacturing Company and those developed by Lee et al[2] are presented and compared. Star Manufacturing Company modified their design procedures in the fall of 1981. The techniques used prior to these modifications, as well as those currently (1982) being used, are discussed and compared to procedures proposed by Lee. This chapter serves as background for Chapter IV where analytical results are compared to test results.

3.2 Star Manufacturing Company Procedure

Star Manufacturing Company's computer design program uses a standard stiffness analysis to determine internal axial forces, shears and moments and external deflections. For analysis purposes, nonprismatic members are divided into a number of segments each with uniform properties. The stiffness matrix is then developed and solutions obtained. Stresses at the mid-point of all segments and at section changes are calculated and standard AISC interaction equations (Formulas 1.6-1a, 1.6-1b or 1.6-2) are used to determine allowable or service load.

Interaction equations are checked at each analysis point and the location with a maximum value less than 1.0 (unity check) is used as a criterion for determining maximum service load. In addition, local buckling and shear failure is checked using AISC provisions.

AISC Formulas 1.6-1 and 1.6-2 were developed for doubly symmetrical H-shaped members of length L, where L is the distance between strong axis brace points. Star Manufacturing Company uses these formulas for prismatic, doubly symmetrical tapered and singly symmetrical tapered members. Checks are made at all analysis points with effective length factors kept constant over the member length L, defined as the distance between member ends or changes in taper.

The basic factor of safety in the AISC specification is 1.67. To determine the ultimate load of the test frames, the service loading was increased until a unity check value of approximately 1.67 was attained for at least one analysis point. This method is not strictly correct, since the interaction equations are nonlinear in form. However, it is believed to be a sufficient measure of frame capacity for the purposes of this study. A typical computer output showing geometry and section property data and the analyses for ultimate full live load loading for Frames 1 and 2 is shown in Appendix B.

As was stated previously, the analysis method currently used by Star Manufacturing Company is the use of AISC interaction equations to predict critical loads on a frame. These interaction equations account for two second order effects; first is the effect of changes in structural geometry (joint displacements) on member forces (P-Delta effect); and second is the influence of axial force on member stiffness. In the AISC interaction equations, the amplification factor $1/\{1-(f_a/F_e')\}$ and the effective length factor (K) are both used to account for these effects. Until the fall of 1981, assumed effective length factors of 1.0 for the major axis of all rafters, 1.5 for the major axis of all exterior columns and 1.0 for the minor axis for all members were used in the Star Manufacturing Company procedures. In the fall of 1981, a rational method of calculating major axis effective length factors based on methods developed by Lee, Ketter and Hsu(2) was implemented.

3.3 Comparison With Lee Procedures

In 1981 the Metal Building Manufacturers Association published Design of Single Story Rigid Frames authored by Lee, Ketter and Hsu(2). This book summarizes all of the pertinent results of research and investigations completed in recent years concerning the design of steel, single story, rigid frames with emphasis on frames with doubly summetrical web tapered members. The material contained in the book is largely a result of research conducted by the authors.

There are many differences between Star Manufacturing Company's current analysis procedure and procedures presented by Lee et al. The principal differences are as follows:

Axial Compression. In the Lee method of axial load analysis, effective length factors are calculated using member stiffnesses with adjustment for the taper ratio. For axial buckling of tapered columns, two sets of effective length factors are provided. The first is for columns having a constant linear variation in depth along the length of the member (web tapered columns). These curves are the basis for the design rules in the 1978 Specification (Appendix D of Reference 7) and are included in the commentary to that document. To qualify under the provisions of the Specification, a tapered member must meet the following requirements: It must be symmetric about the weak axis, the flanges must be of equal and constant area and the depth must vary linearly. The last requirement prevents the use of the Specification in cases where a tapered member is multi-segmented. A second set of curves for columns with multi-segmented tapered members are presented in Appendix E of Reference 2. In both procedures, the effective length factor for the weak axis is obtained by considering the weak direction as prismatic. The end restraint factors are then calculated and the AISC alignment chart used to determine K_y.

For strong axis buckling, the AISC procedure requires the use of charts found in the Commentary, Section D-2, to determine the effective length factor K_γ. If the restraining member at the end of the member is tapered, a modification of the restraining factor, G_T or G_B, must be made. This modification is dependent upon the type of restraining member (ie, multi-tapered or singly-tapered) and the taper ratio(s) of the restraining member. This modification involves procedures presented in Appendices E and C of Reference 2. It should be noted that in the Lee analysis, the calculated KL/r about the major axis is constant for the entire member length. The value for K_γ is based on the smallest radius of gyration about the major axis for the entire member. Thus if major axis buckling controls, the same column slenderness ratio (KL/r) and allowable axial stress value are used for the entire member length.

As was stated previously, Star Manufacturing Company has recently implemented a procedure for determining major axis effective length which is, in part, based on the Lee methods discussed above. The initial intention was to develop an automated procedure, based on Lee's methods, that would circumvent the need for design curves. An attempt was made to automate a procedure for calculating the critical buckling load of a tapered column which was developed by Lee, Morrell, and Ketter[8]. In this method, the slope deflection equations are developed and the coefficients are arranged into a coefficient matrix. The critical buckling load can then be determined using an iterative procedure in which the applied load is incremented until the determinant of the coefficient matrix changes algebraic sign. The effective length factor could then be determined by solving the Euler column buckling equation for K_x. Attempts were made to verify the coefficient matrices developed by Lee but they did not prove successful[9]. Thus the use of these coefficient matrices for determination of effective length factors was abandoned.

Star Manufacturing Company then developed an approximate method for determining major axis effective length factors[10]. This method consists of two steps: first, the pinned-end tapered member is theoretically converted into a prismatic member of different length which has the cross-section of the smaller end of the tapered member; second, the end conditions of the converted prismatic member are considered. The joint stiffness ratios of the member ends are used together with the traditional prismatic column effective length nomographs[7], to determine the major axis effective length factor of the tapered member.

Bending. An important consideration in the lateral-torsional buckling analysis of beams is the influence of end restraint at the brace points. Design provisions in the 1978 AISC Specifications conservatively imply lateral and torsional pinned supports, ignoring the possible restraint from adjacent spans. Reference 2 provides methods to consider this restraint. Curves in Appendix F of this reference permit the calculation of an equivalent length parameter associated with either the uniform torsion term or the warping term, K_s and K_w, respectively, of the classical lateral-torsional buckling equation. The use of these parameters effectively results in a reduction in the unbraced length used for lateral torsional buckling analysis. The Star Manufacturing Company procedure conservatively uses the full unbraced length for analysis.

To account for member taper, Lee has developed length modification factors. The use of these factors, referred to as h_s and h_w, results in an increase in the effective length (weak axis) of a member. These modifications are included in Appendix D of the current AISC Specification. Star Manufacturing Company does not consider the effects of taper on lateral torsional buckling.

Combined Bending and Compression. In Lee's analysis for combined stresses, the interaction equation approach is used. This is the same approach used by Star Manufacturing Company and is presented in Section D4 of the AISC Specification[7]. AISC interaction equations D4-1a and D4-1b are used to determine the critical load on a frame. The equivalent moment coefficient, C_m, used in equation D4-1a, is taken as 0.85 for all cases. However, the commentary to the Specification states that C_m may be taken as

$$C_m = 1.0 - 0.18\ f_a/F_e'$$

for the design of compression members in frames subject to sidesway. In the above equation, F_e' is the Euler buckling stress calculated about the strong axis of the member with a factor of safety of 23/12. The former value of C_m is used in Star Manufacturing Company's design program.

Other Design Considerations. Methodology for determination of the allowable axial stress in a tapered column with unequal flange areas is presented in Appendix G of Reference 2. Only complex charts that require manual interpolation are presented. No algebraic expressions are available to the designer, and the method is not amenable to automation. Star Manufacturing Company's current method does not directly consider the effects of unequal flanges on lateral-torsional buckling.

In determining the effective slenderness ratio, KL/r, Lee in Reference 2 uses the distance from the column base to the knee stiffener or the distance from the peak to the knee connection plate as the member length. The member length used in the Star Manufacturing Company procedure is the distance from joint to joint.

In Reference 2, the bending coefficient, C_b, is conservatively taken as unity although the coefficient may be considerably higher for some cases. Star Manufacturing Company uses a value of 1.0 for all cases except for pinned column analyzed from the base up to the first brace point. A value of 1.75 is used in this region.

CHAPTER IV

TEST RESULTS AND COMPARISONS

4.1 Comparison of Test Results with Star Manufacturing Company Predictions

In this section, test results are compared to Star Manufacturing Company's standard computer design program. The results presented herein do not reflect previously discussed changes that were implemented in August, 1981. Typical test results are shown in Appendix C; complete results are found in References 3 through 6. Results are summarized in Tables 2 through 6. Comparisons are made between predicted and measured deflections, stresses and critical loads.

4.1.1 Frames 1 and 2 - SRL04 50 20/25 16/25

Initial Test, Full Live Load, Frame 1. For this test 4.0 kips was applied at each load point on the frame (3.07 kips corresponds to a unity check value of 1.0 at service loads). Excellent agreement was found between predicted and measured vertical centerline deflection. The measured sidesway deflection was not in agreement with the predicted values, especially after 3 kips load. However, the difference is small and can be considered insignificant.

Lateral deflections of the inside and outside flanges of the east frame were significant. Maximum lateral deflection was approximately 1.06 in. near the centerline of the rafter, indicating potential lateral buckling.

Table 2
Full Live Load Test Results

Frame Designation	Frame No.	Centerline Vertical Deflection, in.		Sidesway Deflection, in.		Maximum Load, Kips		Notes
		Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	
SRLO4 50 20/25 16/25	1	3.79	4.05	0.50	0.11	5.13	4.75	
	2	3.35	3.87	0.47	0.30	5.29	4.80	Deflections are for a load of 4.5 kips.
SR4 60 40/25 20/20	3	3.87	3.48	0.52	0.20	4.50	5.76	Nonstandard Flange Brace Spacings
	4	5.03	4.69	0.61	0.26	7.59	7.50	
STR 60 12/25 10/25	5	3.69	4.43	-	-	4.17	3.40	Deflections are for a load of 3.0 kips.
	6	3.82	3.85	-	-	3.98	3.00	
STR4 50 12/25 14/25	7	3.79	3.79	-	-	N.A.	2.10	Nonstandard Flange Brace Spacings
	8	3.25	3.16	-	-	-	1.80	Loaded to Working Load Only.

Frame Designation	Frame No.	Avg. Stress in Column at Knee		Avg. Stress in Rafter at Knee		Avg. Stress in Rafter at Peak		Notes
		Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	
SRLO4 50 20/25 16/25	1		28.78		27.26		35.02	
	2		24.07		39.44		30.89	Stresses @ Load = 4.5 kips
SR4 60 40/25 20/20	3	21.84	24.23	33.18	27.14	27.22	25.20	Nonstandard Flange Brace Spacings
	4	28.20	33.51	41.85	yielded	35.40	29.83	
STR 60 12/25 10/25	5	35.40	26.47	36.16	28.86	30.30	23.57	Stresses measured at a load of 3.0 kips
	6	35.81	24.15	36.89	23.64	30.81	24.87	
STR4 50 12/25 14/25	7	26.20	19.14	22.50	15.23	29.80	27.84	Nonstandard Flange Brace Spacings
	8	23.12	14.94	19.70	17.69	26.20	22.19	Stresses at working load

Note: All stresses in ksi units

Table 3
Unbalanced Live Load Test Results

Frame Designation	Frame No.	Centerline Vertical Deflection, in.		Sidesway Deflection, in.		Maximum Load, Kips		Notes
		Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	
SRLO4 50 20/25 16/25	1	-	-	-	-	-	-	
	2	-	-	-	-	-	-	
SR4 60 40/25 20/20	3	1.51	1.25	1.22	0.98	-	4.5	Not loaded to failure
	4	1.52	1.40	1.23	1.05	-	4.5	Not loaded to failure
STR 60 12/25 10/25	5	-	-	-	-	-	-	
	6	-	-	-	-	-	-	
STR4 50 12/25 14/25	7	2.78	2.78	0.73	0.57	-	3.0	Not loaded to failure
	8	2.76	2.64	0.71	0.52	-	3.0	Not loaded to failure

Frame Designation	Frame No.	Avg. Stress in Column at Knee		Avg. Stress in Rafter at Knee		Avg. Stress in Rafter at Peak		Notes
		Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	
SRLO4 50 20/25 16/25	1	-	-	-	-	-	-	
	2	-	-	-	-	-	-	
SR4 60 40/25 20/20	3	9.23	6.67	14.36	9.56	10.13	7.76	Not loaded to failure
	4	11.25	9.99	11.03	7.57	11.25	8.19	Not loaded to failure
STR 60 12/25 10/25	5	-	-	-	-	-	-	
	6	-	-	-	-	-	-	
STR4 50 12/25 14/25	7	20.9	14.07	15.6	10.15	22.6	18.42	Not loaded to failure
	8	19.3	12.47	17.6	13.92	21.6	18.27	Not loaded to failure

Note: All stresses in ksi units

Table 4

Lateral Load Test Results

Frame Designation	Frame No.	Centerline Vertical Deflection, in.		Sidesway Deflection, in.		Maximum Load, Kips		Notes
		Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	
SRLO4 50 20/25 16/25	1	-	-	-	-	-	-	
	2	-	-	-	-	-	-	
SR4 60 40/25 20/20	3	0.11	0.14	1.33	1.48	-	6.0	Not loaded to failure
	4	0.11	0.20	1.33	1.48	-	6.0	Not loaded to failure
STR 60 12/25 10/25	5	-	-	-	-	-	-	
	6	-	-	-	-	-	-	
STR4 50 12/25 14/25	7	0.04	0.18	3.61	3.19	-	8.08	Not loaded to failure
	8	0.03	0.31	3.61	3.23	-	8.08	Not loaded to failure

Frame Designation	Frame No.	Avg. Stress in Column at Knee		Avg. Stress in Rafter at Knee		Avg. Stress in Rafter at Peak		Notes
		Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	
SRLO4 50 20/25 16/25	1	-	-	-	-	-	-	
	2	-	-	-	-	-	-	
SR4 60 40/25 20/20	3	-	-	-	-	-	-	
	4	-	-	-	-	-	-	
STR 60 12/25 10/25	5	-	-	-	-	-	-	
	6	-	-	-	-	-	-	
STR4 50 12/25 14/25	7	21.72	14.36	17.77	9.72	0.26	1.45	Stresses measured at a load of 6.86 kips
	8	21.33	12.76	20.97	12.91	0.65	2.47	Stresses measured at a load of 6.86 kips

Note: All stresses in ksi units

Table 5
Combined Unbalanced Live Load (Windward Side) with Lateral Load Test Results

Frame Designation	Frame No.	Centerline Vertical Deflection, in		Sidesway Deflection, in.		Maximum Load, Kips ULL/WL		Notes
		Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	
SRL04 50 20/25 16/25	1	-	-	-	-	-	-	
	2	-	-	-	-	-	-	
SR4 60 40/25 20/20	3	2.12	1.85	2.89	2.80	6.0/10.0	6.0/7.0	Deflections measured at a load of 6.0/5.75 kips
	4	2.12	1.78	2.91	2.80	6.0/10.0	6.0/7.0	Deflections measured at a load of 6.0/5.75 kips
STR 60 12/25 10/25	5	-	-	-	-	-	-	
	6	-	-	-	-	-	-	
STR4 50 12/25 14/25	7	1.88	1.67	2.27	2.07	-	2.0/4.65	Not loaded to failure
	8	1.86	1.81	2.25	2.13	-	2.0/4.65	Not loaded to failure

Note: ULL - Unbalanced Live Load on Windward Side
WL - Wind Load

Frame Designation	Frame No.	Avg. Stress in Column at Knee		Avg. Stress in Rafter at Knee		Avg. Stress in Rafter at Peak		Notes
		Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	
SRL04 50 20/25 16/25	1	-	-	-	-	-	-	
	2	-	-	-	-	-	-	
SR4 60 40/25 20/20	3	16.32	12.35	24.66	18.13	13.78	11.74	Stresses measured at a load of 6.0/4.0 kips
	4	6.23	5.69	8.35	4.87	15.77	13.5	Stresses measured at a load of 6.0/5.75 kips
STR 60 12/25 10/25	5	-	-	-	-	-	-	
	6	-	-	-	-	-	-	
STR4 50 12/25 14/25	7	1.3	0.15	1.6	0.0	14.9	11.89	Not loaded to failure
	8	27.3	18.27	26.0	18.42	13.9	10.59	Not loaded to failure

Note: All stresses in ksi units

Table 6
Combined Unbalanced Live Load (Leeward Side) with Lateral Load Test Results

Frame Designation	Frame No.	Centerline Vertical Deflection, in		Sidesway Deflection, in.		Maximum Load, Kips ULL/WL		Notes
		Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	
SRL04 50 20/25 16/25	1	-	-	-	-	-	-	
	2	-	-	-	-	-	-	
SR4 60 40/25 20/20	3	-	-	-	-	-	-	
	4	-	-	-	-	-	-	
STR 60 12/25 10/25	5	-	-	-	-	-	-	
	6	-	-	-	-	-	-	
STR4 50 12/25 14/25	7	2.71	2.64	0.88	0.80	-	3.0/3.37	Not loaded to failure
	8	2.69	2.63	0.86	0.89	-	3.0/3.37	Not loaded to failure

Note: ULL - Unbalanced Live Load on Leeward Side
WL - Wind Load

Frame Designation	Frame No.	Avg. Stress in Column at Knee		Avg. Stress in Rafter at Knee		Avg. Stress in Rafter at Peak		Notes
		Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	
SRL04 50 20/25 16/25	1	-	-	-	-	-	-	
	2	-	-	-	-	-	-	
SR4 60 40/25 20/20	3	-	-	-	-	-	-	
	4	-	-	-	-	-	-	
STR 60 12/25 10/25	5	-	-	-	-	-	-	
	6	-	-	-	-	-	-	
STR4 50 12/25 14/25	7	6.7	6.53	7.3	6.24	21.4	17.5	Not loaded to failure
	8	33.3	21.46	27.8	19.14	22.2	17.4	Not loaded to failure

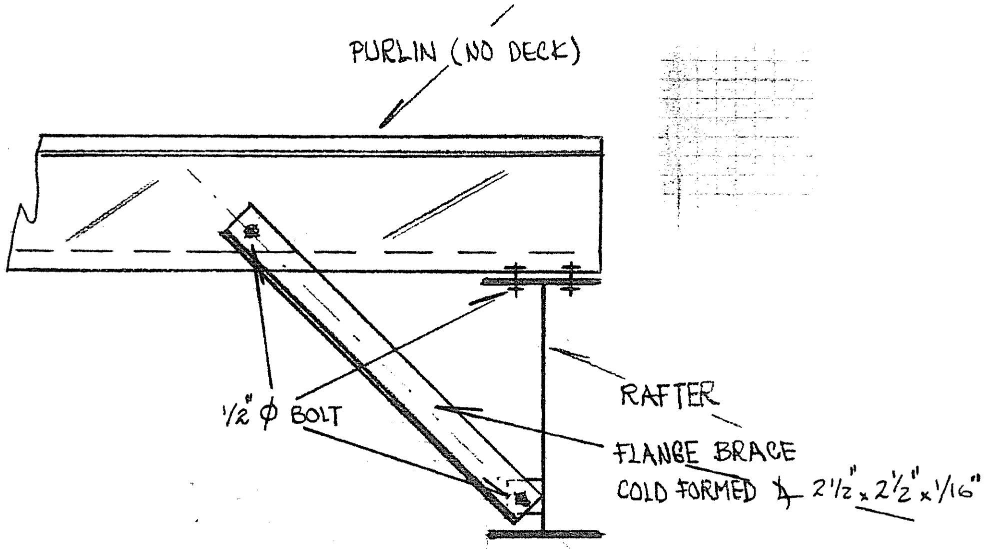
Note: All stresses in ksi units

Comparisons between predicted stresses and stresses computed from measured strains at locations in the south column near the knee, south rafter near the knee and the south rafter near the peak show excellent agreement. (Measured strains were multiplied by E = 29,000,000 psi to obtain stresses below the yield stress of the material. If the computed stress exceeded the yield stress the yield stress is used).

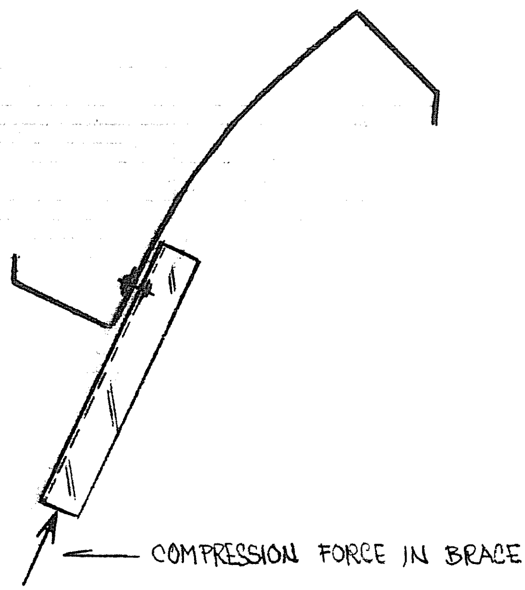
Results of this test indicate that frame stiffness and stress distributions are accurately predicted by Star Manufacturing Company's design program.

Final Test, Frame 1. Test results for Frame 1 loaded with full live load are shown in Table 2. Failure occurred by lateral buckling of the north rafter near the knee at a load of 4.75 kips. A unity check value of 1.67, as determined using Star Manufacturing Company's design program, corresponds to a load of 5.13 kips. Output is shown in Figure B.2 and the critical location is in the rafters, near the knee. Lateral buckling occurred because of failure of the rafter compression (lower) flange brace near the north knee. The roof sheeting did not extend to the purlin supporting the flange brace and the purlin rolled as shown in Figure 10, effectively eliminating the brace and permitting lateral buckling.

As shown in Table 2, good agreement was attained between measured and predicted vertical centerline deflection. The maximum lateral deflection was 0.6 in. and



a) Flange Brace



b) Failure Mode

Figure 10. Failure of Compression Flange Brace, Frame 1

occurred near the location of the failed brace. Predicted stress and stress calculated from measured strain data is shown in Table 2 for the south column near the knee, the south rafter near the peak, and the south rafter near the peak. Reasonable agreement was obtained between the predicted stresses and experimentally obtained stresses for the column knee and rafter peak locations. Stresses in the rafter near the knee were much lower than predicted.

Results of this test indicate that the design procedure accurately predicts the stiffness of the frame and stress distributions within the frame. Failure of the frame was caused by an inadequate compression flange brace near the north knee.

Final Test, Full Live Load, Frame 2. Before conducting the test on Frame 2, roof sheeting was attached to the entire roof area. End wall sheeting was not used. Frame 2 was then subjected to full live load until failure by lateral buckling in the south rafter at a load of 4.8 kips at each location. Lateral movement was visually more evident along the inside (peak) rafter segment, however, it was apparent that the outside (knee) rafter segment also moved laterally. Output from the Star Manufacturing Company's program for the test condition is shown in Figure B.3. The predicted failure load for this analysis was 5.29 kips.

Predicted and measured vertical deflection at the centerline is shown in Table 2. The measured deflections were about 15% higher than predicted. The maximum lateral deflection before failure was 0.49 in. Experimentally determined and predicted stresses are shown in Table 2. Fair agreement was obtained between the experimentally determined and predicted values except for the north column near the knee.

Results of this test indicate that Star Manufacturing Company's design program adequately predicts frame stiffness and internal stress distributions. The roof sheeting was found to have sufficiently stiffened the purlin so that the type of failure shown in Figure 10 was prevented. It is believed that the frame failed below the predicted ultimate load because of damage caused by the failure of Frame 1. When the lateral brace failed during the Frame 1 test, the rafter segments of Frame 2 were pushed laterally at the flange brace locations. The rafter segments remained in a laterally deflected position when the load on Frame 1 was removed.

Coupon Tests, Frames 1 and 2. Upon completion of all testing, samples of the plate material used to fabricate the frames were removed at several locations on the frame. The locations were chosen to minimize the effects of possible yielding due to test loading. Standard ASTM E-8-57 T tensile coupons were then machined and tested. Measured yield stresses varied from 47.9 to 66.3 ksi. The higher values were found in the web material and the lower values in the flange material. The results for the flanges were sufficiently close to the specified minimum yield stress, 50 ksi to be acceptable. (A yield stress of 50 ksi was used in the Star Manufacturing Company computer analyses.)

4.1.2 Frames 3 and 4 - SR4 60 40/25 20/20.

Initial Test, Unbalanced Live Load, Frames 3 and 4. Test results and theoretical predictions from Star Manufacturing Company's design program are shown in Table 3 for both frames subjected to the unbalanced live load shown in Figure 5a. For this test, 4.5 kips was applied at each load point on each frame representing approximately the working load for the frames, e.g., a unity check value of 1.0. Table 3 shows experimental and theoretical deflection data for vertical centerline deflection and sidesway deflection. The measured centerline and sidesway deflections were slightly less than the predicted values. The predictions are based on perfectly pinned columns which was not achieved in the test set-up and could explain the discrepancy in the sidesway deflections. Maximum lateral deflection was approximately 0.1 in. and is not considered to be significant. Measured stresses were all lower than those predicted by Star's Analysis program.

Results of this test indicate that frame stiffness is adequately predicted by Star Manufacturing Company's design program.

Initial Test, Lateral Load Only, Frames 3 and 4. Test results for both frames subjected to a concentrated lateral load near the knee reentrant corner of the south columns are given in Table 4. Approximately 6.0 kips was applied horizontally to each frame simultaneously. Centerline and sidesway deflection data is shown in Table 4. Excellent agreement was obtained between the measured and theoretical sidesway deflections. Centerline deflection was higher than predicted but this is not considered to be of significance. The maximum lateral displacement was approximately 0.1 in. and is not considered significant.

This test shows that the design program adequately predicts sidesway stiffness of frames.

Initial Test, Unbalanced Load Live (Windward Side) and Lateral Load, Frames 3 and 4. For this test both frames were loaded simultaneously with unbalanced live load and lateral load as shown in Figure 5c. First, 5.0 kips simulated live load was applied at each load point in 1.0 kip increments and then 7.0 kips lateral load in 1.0 kip increments was applied simultaneously near the reentrant corner at the knee of the south columns. After each lateral load increment, the gravity load was adjusted to 5.0 kips and then the data was recorded. Test results showed good agreement between predicted and measured centerline vertical deflections and sidesway deflections (Reference 4). The maximum lateral displacement was approximately 0.25 in. and is not considered to be significant. Excellent agreement was obtained between predicted and experimental stresses(4). Strain readings were converted to stress assuming a modulus elasticity of 29,000 ksi.

Test results indicate that the design program adequately predicts frame stiffness under combined loadings. Stress predictions were also excellent.

Final Test, Full Live Load, Frame 4. Test results for Frame 4 loaded with full live load are shown in Table 2. The maximum load applied was 7.5 kips at each location. This load corresponds to a unity check value of 1.65 as determined using Star Manufacturing Company's design program. Star's computer design program predicted the critical location was in the southwest rafter at the knee(4). As shown in Table 2, good agreement was attained between measured and predicted vertical centerline deflection. It is evident from the load vs. centerline deflection plot (Reference 4) that the frame could have taken more load. However, the frame was unloaded because a strain gage indicated yielding of the rafter near the knee. The maximum lateral deflection was 0.35 in. near the peak. This deflection is not considered to be of significance.

Predicted stress and stress calculated from measured strain data is shown in Table 2 for the north column near the knee, the north rafter near the knee, the north rafter near the peak. Reasonable agreement was obtained between the predicted stresses and experimentally obtained stresses until near the maximum load. When the maximum load was approached, the stresses measured near the knee became greater than predicted. The deviation of the measured stresses indicates that the frame was approaching its capacity.

Results of this test indicate that the design procedure accurately predicts the stiffness of the frame, stress distributions within the frame, and is a reasonable estimate of the capacity of the frame for full live load.

Final Test, Unbalanced Live Load (Windward Side) and Lateral Load, Frames 3 and 4. Table 5 shows results for 6.0 kips unbalanced live load combined with lateral load applied simultaneously to both frames. For this test, the unbalanced live load was applied in 1.0 kip increments to 6.0 kips (at each load location). Lateral load was then applied while the unbalanced live load was maintained at the 6.0 kip level. Failure occurred at 7.0 kips of lateral load by lateral buckling of the southwest rafter compression (lower) flange. The predicted failure load using Star Manufacturing Company's design program was 6.0 kips unbalanced live load and 10.0 kips lateral load. Because failure was not expected, no data was obtained beyond 5.75 kips of lateral load.

Vertical centerline deflection and sidesway deflection data are shown in Table 5. Sidesway deflections were in excellent agreement with predicted values. The measured centerline deflections were slightly less than those predicted.

The maximum measured lateral displacement of Frame 1 was 0.4 in. and the maximum lateral displacement of Frame 2 was 1.5 in. The lateral buckle was clearly seen in plots of the deflected shape (Reference 4).

Predicted and measured stresses are shown in Table 5. Good to excellent agreement was obtained at all locations except near the knee in the rafter of Frame 4.

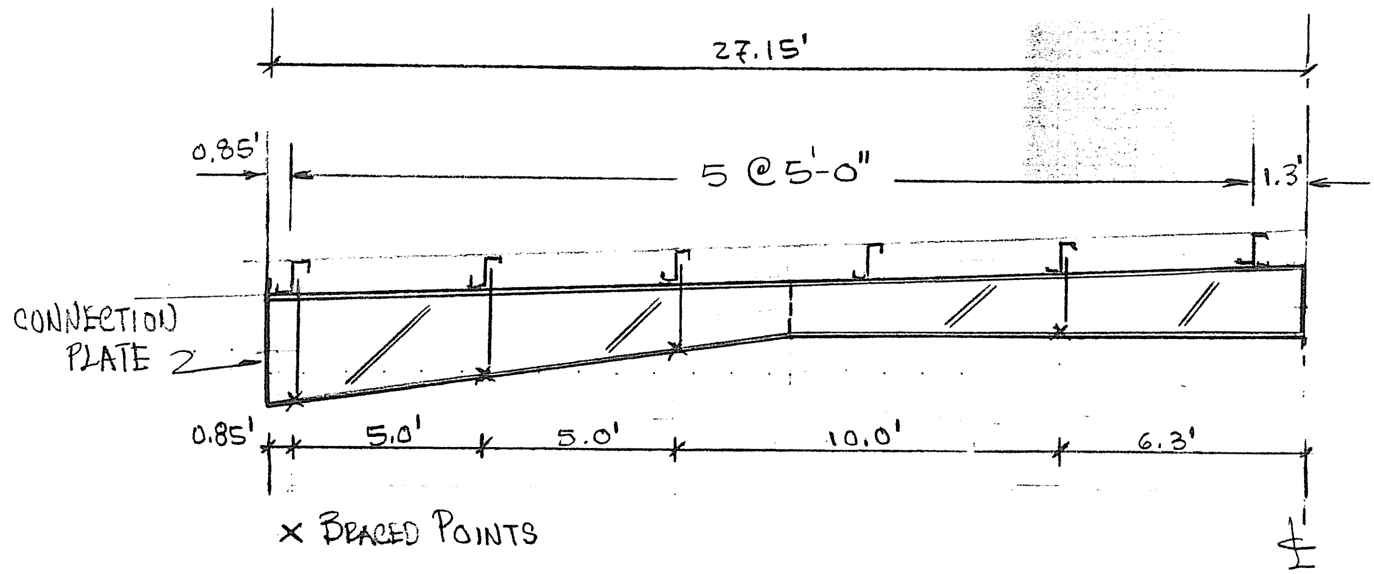
The experimentally obtained failure load from this test is not in close agreement with the predicted failure load. A possible explanation is that Frame 4 was yielded locally by the application of full live load to a unity check value of 1.65 as described previously.

Although the predicted failure load was 6.0 kips live load plus 10.0 kips lateral load, the west frame was only able to resist 6.0 kips live load and 7.0 kips lateral load. Load versus stress plots (Reference 4) show that the stress in the rafter section near the lateral buckle was close to maximum from the application of the 6.0 kips live load. The rate of change of stress at this location is very small relative to the applied lateral load. Hence, the rafter near the peak was subjected to a very high stress level from the live load application and additional lateral load only increased the stress slightly. If the rafter was near failure due to the live load, a large discrepancy in the predicted lateral failure load is expected. In other words, because the stress in the rafter section is near maximum and the rate of change of that stress to applied lateral load is very small, the rafter may be expected to fail over a relatively wide range of lateral load.

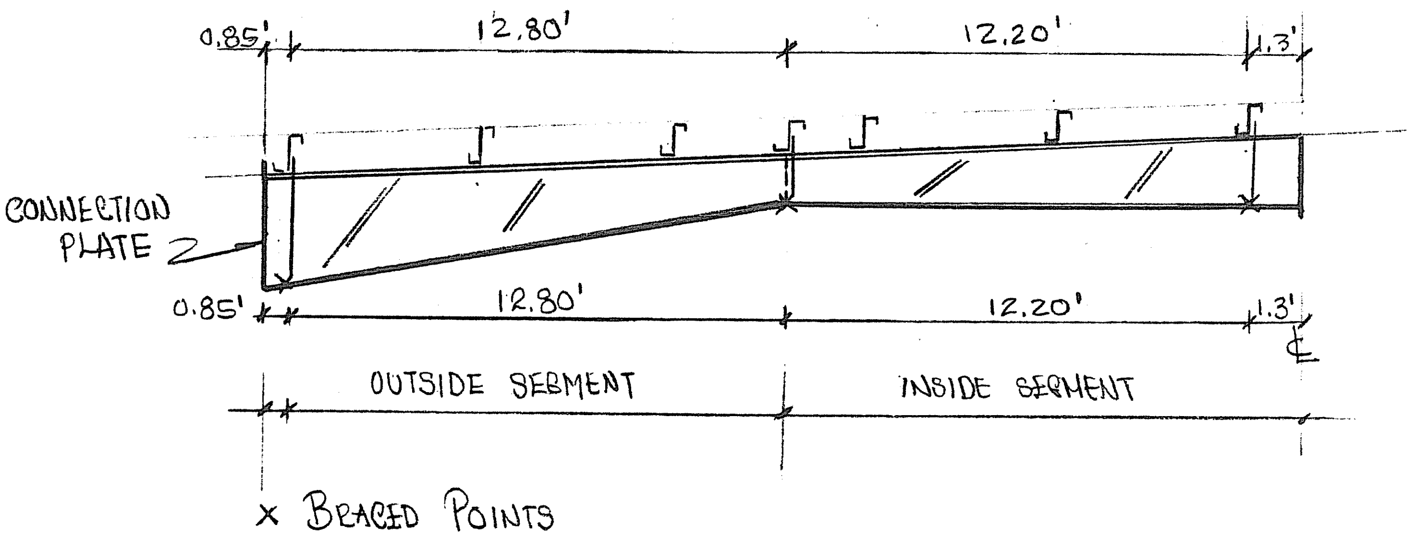
Final Test, Full Live Load, Frame 3 With Nonstandard Flange Brace Spacing. To investigate the effects of different lateral bracing schemes on the lateral buckling behavior of the rafters the locations of the lower flange braces were changed on the east frame as shown in Figure 11. In addition, the purlin connections to the top flanges were removed except directly over the flange braces. Consequently, the outside rafter segments were fully braced near the knee and at the transition location and the inside rafter segments were braced at the transition section near the peak. The frame was subjected to full live load and failed by lateral buckling in the south rafter at a load of 5.8 kips at each load location. Lateral movement was visually more evident in the outside segment, however, it was apparent that the inside segment also moved laterally.

Output from the Star Manufacturing Company's computer program for the test condition gives a predicted failure load for this analysis of 4.5 kips.

Predicted and measured vertical deflection at the centerline is shown in Table 2. Good agreement was obtained between the measured and predicted deflections. The maximum



a) Standard Flange Bracing



b) Modified Flange Bracing

Figure 11. Standard and Modified Flange Bracing, Frame 3

lateral deflection was 0.75 in. and the buckled configuration was clearly seen in plots of the deflected shape of the frame (Reference 4). Experimentally determined and predicted stresses are shown in Table 2. Excellent agreement was obtained between the experimentally determined and predicted values.

Results of this test show that Star's computer analysis gives conservative results (ie., low failure load) when the lateral bracing is arranged such that lateral buckling controls.

Coupon Tests, Frames 3 and 4. Upon completion of all testing, samples of the plate material used to fabricate the frames were removed at several locations. The locations were chosen to minimize the effects of possible yielding due to test loadings. Standard ASTM E-8-57T tensile coupons were then machined and tested. Measured yield stresses varied from 47.2 to 58.3 ksi. The lowest yield levels were found in the south column of Frame 4 and did not affect the test results. The remaining results were sufficiently close to the specified minimum yield stress, 50 ksi, to be acceptable.

For the Star Manufacturing Company computer analyses, a conservative yield stress of 50 ksi was used in all cases.

4.1.3 Frames 5 and 6 - STR 60 12/15 10/25

Full Live Load, Frame 5. Test results for Frame 5 loaded with full live load are shown in Table 2. The frame was loaded to 2.95 kips at which time yielding was observed in the compressive flange of the rafter near the peak. Upon inspection of the frame, it was noticed that the bolts at both the knee and peak splices had not been sufficiently tightened. The bolts were tightened and the frame reloaded to an ultimate failure load of approximately 3.4 kips. Failure was manifested by local buckling of the compressive flange of the rafter near the peak. The failure load attained and the location of failure are not in good agreement with Star Manufacturing Company's design program. The program predicted an ultimate load of 4.17 kips with the critical location being in the south rafter at the knee.

The low failure load and unexpected critical location can best be explained by the following logic. When the frame was loaded the first time, the bolts were not tightened sufficiently and thus the ends were free to rotate (i.e., act as pinned-ends). If a simple beam analysis of the rafter is done assuming simple supports, it is found that the location of maximum bending stress is between the two centermost loading points. Through this analysis, the stress in the aforementioned region would be approximately 65 ksi at a load of 2.95 kips. This could explain the yielding that occurred in the first loading sequence. Since 65 ksi is greater than the yield stress of the material, residual stresses must have remained after the unloading of the frame. Thus, after the bolts were tightened and the frame loaded for the second time, the residual stresses combined with the loading stresses, resulting in premature failure of the frame.

Test results given in Table 2 are for the second loading sequence. As can be seen in Table 2, measured centerline vertical deflections were about 20% higher than those predicted. The maximum lateral deflection was 0.15 in. near the southeast knee. This deflection is not considered to be of significance.

Predicted stresses and stresses calculated from measured strain data are shown in Table 2 for the south column near the knee, the south rafter near the knee, and the south rafter near the peak. Experimentally obtained stresses were generally lower than predicted stresses. However, the stress measured on one side of the peak was in close agreement with the predicted stress at that point.

Results of this test indicate that premature failure of the east frame was predicted by shortcomings in the erection procedure rather than inaccuracies in the design procedure.

<u>Full Live Load, Frame 6</u>. Tests results for the west frame with standard flange bracing loaded with full live load are given in Table 2. The frame was loaded to 3.0 kips at which time areas of yielding were observed on the compressive flange of the rafter near the peak. Upon further inspection it was noticed that local buckling of the inside (compressive) flange of the southwest rafter had occurred

near the knee. The failure load of 3.0 kips did not compare well with Star Manufacturing Company's design program. The program predicted the failure load to be 3.98 kips and the critical location was in the southwest column at the knee.

As shown in Table 2, excellent agreement was attained between measured and predicted centerline vertical deflection. The maximum lateral deflection was 0.19 in. at the peak. This deflection is not considered to be of significance.

Predicted stress and stress calculated from strain data is given in Table 2 for the north column near the knee, the north rafter near the knee, and the north rafter near the peak. All experimentally obtained stresses were lower than those predicted by Star Manufacturing Company's design program.

As was pointed out in Reference 5, the west frame rafter was erected with the centerline of the lower flange approximately 1 in. outside the theoretical plane of the web. The resulting eccentricity of vertical load with respect to the centroid created torsional stresses in the rafter which are not considered in Star's design program. This could account for the discrepancies between the experimental and predicted results.

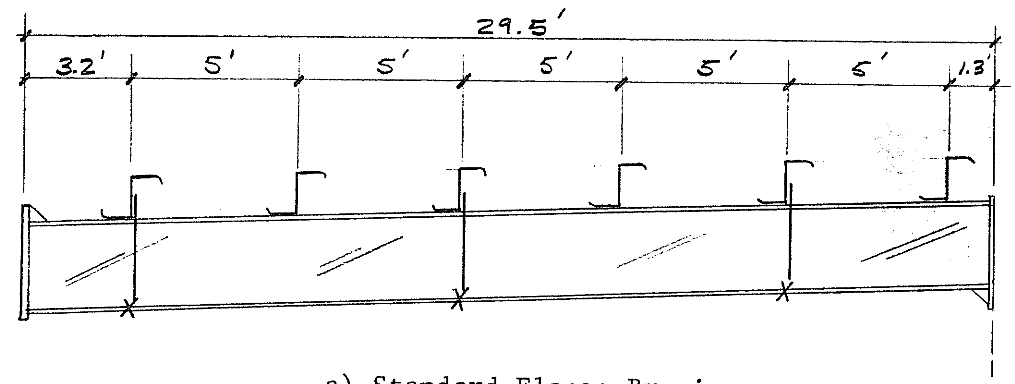
Full Live Load, Frame 6, Nonstandard Bracing Scheme 1. This test was designed to investigate the affect of different lateral bracing schemes on the lateral buckling behavior of the rafters and to study the brace forces introduced at the ends of the unbraced span. Figure 12b shows the bracing pattern which was tested. This bracing scheme was designed so that the expected failure mode would be lateral buckling of the 20 ft. unbraced span. A critical load analysis using Star's program was not possible because of the excessive weak axis column slenderness ratio.

The frame was loaded to a failure load of 3.1 kips. The failure mode was torsional buckling of the unbraced span rather than the lateral buckling which had been expected. In Reference 5, it was shown that the rafter flanges moved laterally in an almost equal but opposite manner. This suggests that the rafter failed by twisting about a vertical axis. However, since the rafter web was initially out of its vertical plane, the system might not have failed by torsional buckling had this initial eccentricity been minimized. Therefore, it could be assumed that the lateral buckling load of the system would probably exceed the 3.1 kip load attained.

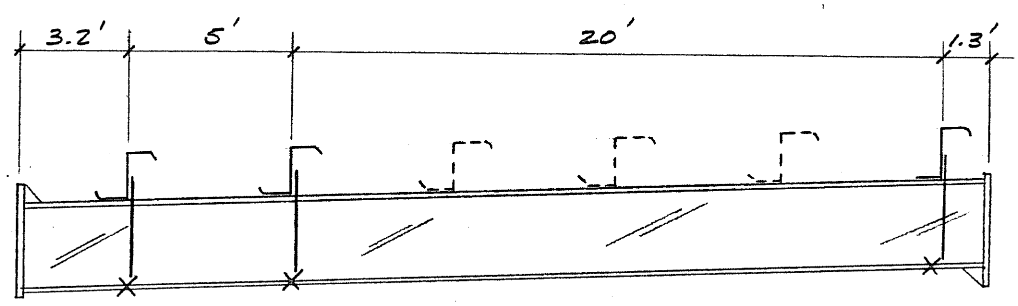
Measured centerline vertical deflections were in close agreement with those predicted by Star Manufacturing Company's design program.

The brace force, measured at both ends of the unbraced span, gave a maximum value of approximately 1.0 kips at the failure load. The braces used at these positions were dynamometers calibrated to measure brace force.

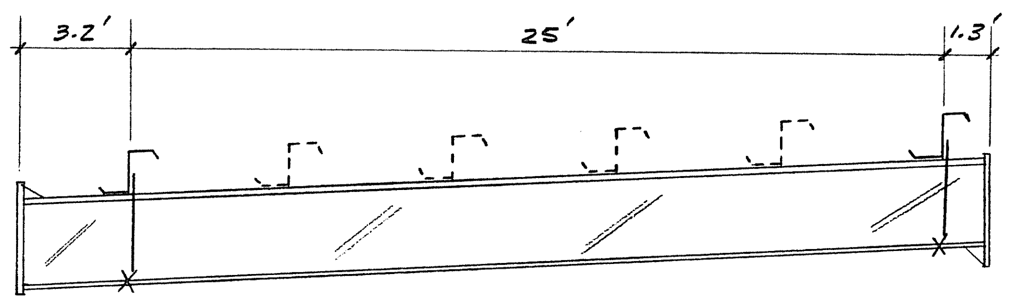
Full Live Load, Frame 6, Nonstandard Bracing Scheme 2. This test was the second of two tests which were designed to



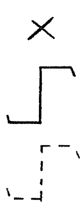
a) Standard Flange Bracing



b) Nonstandard Bracing Scheme 1



c) Nonstandard Bracing Scheme 2



Braced points

Purlin bolted to top flange

Purlin disconnected from top flange

Figure 12. Standard and Modified Flange Bracing, Frame 6

investigate the lateral buckling behavior of the rafters under varied bracing patterns and to study the brace forces introduced at the ends of the unbraced span. Figure 12c shows the bracing pattern which was tested. This bracing scheme was designed such that the expected failure mode would be lateral buckling of the 25 ft. unbraced span. As before, a critical load prediction was not possible using Star's design program due to the excessive weak axis column slenderness ratio.

The frame was loaded to a failure load of 3.0 kips. As in the previous tests, the failure mode was torsional buckling of the unbraced span rather than lateral buckling as was expected. In Reference 5, it was shown, as in the previous test, that the rafter twisted about its vertical axis thus failing by torsional buckling. As was mentioned for the previous test, the rafter would not have failed in this manner if the web had been initially vertical. It is probable that the frame could have attained a higher failure load if the resulting torsional moment had not been present.

Measured centerline vertical deflections were in close agreement with those predicted by Star Manufacturing Company's design program. The maximum brace force measured was approximately 0.9 kips at the failure load. The braces used at these positions were dynamometers calibrated to measure brace forces.

<u>Coupon Tests, Frames 5 and 6</u>. Upon completion of the testing of Frame 5, two samples of the plate material

used to fabricate the frame were removed from the following locations: 1) Coupon No. 1 was removed from the upper flange of the south rafter approximately midway between the peak and knee connections; 2) Coupon No. 2 was removed from the lower flange of the rafter approximately midway between the peak and rafter connections. These locations were chosen to minimize the effects of possible yielding due to test loading. Standard ASTM E-8-47T tensile coupons were then machined and tested. Measurement of the yield stress of Coupon No. 1 was impossible due to premature failure of the attached strain gages. The measured yield stress of Coupon No. 2 was 55.2 ksi. For the Star Manufacturing Company computer analyses, a yield stress of 55 ksi was used in all cases.

4.1.4 Frames 7 and 8 - STR4 50 12/25 14/25

Initial Test, Full Live Load, Frame 8. Test results and theoretical prediction from Star Manufacturing Company's design program are shown in Table 2. The maximum load applied was 1.80 kips at each loading point. This load is approximately the service load for the frame and corresponds to a unity check value of 1.02 as determined using Star's design program.

As shown in Table 2, excellent agreement was attained between measured and predicted vertical centerline deflections. The maximum lateral deflection was 0.20 in. near the peak. This deflection is not considered to be of significance.

Comparisons between predicted and experimental stresses can be found in Table 2. Experimental stresses in the column at the knee connection were lower than predicted. However, the stresses in the rafter were in good agreement with those predicted. Strain readings were converted to stress assuming a modulus of elasticity of 29,000 ksi.

Results of this test indicate that frame stiffness is adequately predicted by Star Manufacturing Company's design program.

Initial Test, Unbalanced Live Load, Frames 7 and 8. Test results and theoretical predictions from Star Manufacturing Company's design program are shown in Table 3 for both frames subjected to the unbalanced live load shown in Figure 5a. For this test, 3.0 kips was applied at each load point on each frame representing approximately the working load for the frames.

Table 3 lists experimental and predicted centerline deflection and sidesway deflection. Excellent agreement was found between predicted and measured vertical deflections. The sidesway deflections were approximately 75% of their predicted values. The predicted sidesway deflections are based on perfectly pinned columns which was not achieved in the test set-up and could explain the discrepancy in the sidesway deflections. Maximum lateral deflection was approximately 0.12 in. and is not considered to be significant.

Predicted and experimental stresses can be found in Table 3. Stresses ranged from 65 to 85% of their predicted values.

This test shows that the design program is slightly conservative in predicting both the sidesway stiffness of frames and the stiffness developed by an unbalanced live loading.

<u>Initial Test, Lateral Load Only, Frames 7 and 8</u>. Test results for both frames subjected to a concentrated lateral load at the knee of the south column are given in Table 4. Approximately 8.0 kips was applied horizontally to each frame simultaneously. Sidesway deflection data is shown in Table 4. Measured sidesway deflections were approximately 89% of the predicted values.

Lateral deflection data on both the inside and outside flanges of both frames showed the maximum lateral displacement to be approximately 0.14 in. which is not considered significant.

Predicted and experimental stres data are given in Table 4. Experimental stresses were substantially lower than their predicted values.

This test shows that the design program is slightly conservative in predicting the sidesway stiffness of frames and very conservative in predicting the stresses developed by lateral loading.

<u>Initial Test, Unbalanced Live Load (Windward Side) and Lateral Load, Frames 7 and 8</u>. For this test both frames were loaded as shown in Figure 5c. First, 2.0 kips simulated live load was applied at each load point in 0.5 kip increments

and then approximately 4.65 kips lateral load in 0.93 kip increments was applied simultaneously at the knee of the south columns. After each lateral load increment, the gravity load was adjusted to 2.0 kips and then the data was recorded.

Table 5 shows good agreement between predicted and measured centerline vertical deflections and sidesway deflections. Lateral deflection data for the outside and inside flanges of both frames shows the maximum lateral displacement was 0.1 in. which is not considered significant[16]. Table 5 gives measured and predicted stresses. Experimental stresses ranged from 69 to 85% of those predicted.

Test results indicate the design program is conservative in predicting the stresses in the frame under combined loading.

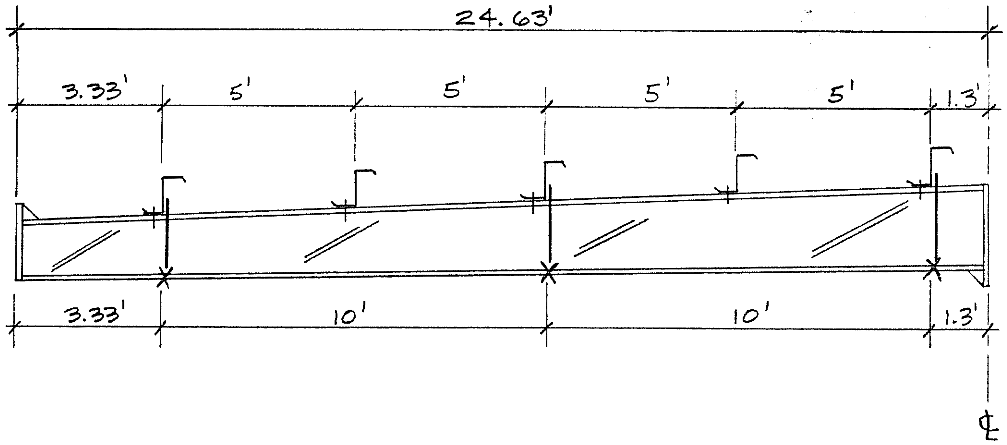
Initial Test, Unbalanced Live Load (Leeward Side) and Lateral Load, Frames 7 and 8. Test results for this loading are shown in Table 6. For this test both frames were loaded simultaneously with unbalanced live load and lateral load as shown in Figure 5d. First, 3.0 kips simulated live load was applied at each load point in 1.0 kip increments and then 3.37 kips lateral load was applied in varying increments. After each lateral load increment, the gravity load was adjusted to 3.0 kips and then the data was recorded.

Data in Table 6 shows excellent agreement between measured and predicted centerline vertical deflections and sidesway deflections. Lateral deflection data for both the outside and inside flanges of both frames show the maximum lateral displacement to be approximately 0.10 in. which is not considered to be significant. Predicted stresses and stresses calculated from measured strains areshown in Table 6. The measured stresses ranged from 72 to 92 percent of their predicted values.

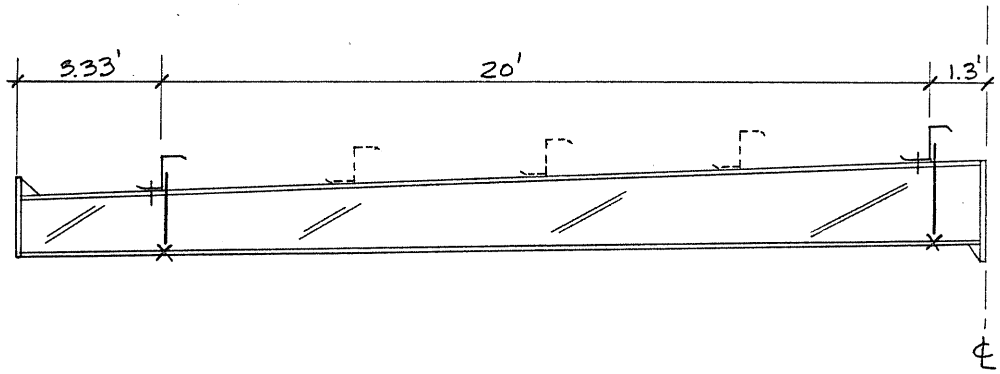
Results of this test indicate that the design program is conservative in estimating the stresses produced by this combined loading.

Final Test, Unbalanced Live Load (Leeward Side) and Lateral Load, with Nonstandard Flange Brace Spacings, Frames 7 and 8. This test was designed to investigate the effect of nonstandard and lateral bracing on the lateral buckling behavior of the rafters. The locations of the flange braces were changed on the south rafter of Frame 8 as shown in Figure 13. In addition, the purlins were disconnected from the top flanges except directly over the flange braces. Consequently, an unbraced span of 20 feet was developed for testing.

For this test both frames were loaded simultaneously with unbalanced live load and lateral load as shown in Figure 5d. First, 1.5 kips simulated live load was applied at each load point in 0.5 kip increments and then 7.5 kips lateral load was applied in varying increments. After each lateral loading, the gravity load was adjusted to 1.5 kips and then the data was recorded.



a) Standard Flange Bracing



b) Modified Flange Bracing

X Braced Points

Purlin Bolted to Top Flange

Purlin Disconnected From Top Flange

Figure 13. Standard and Modified Flange Bracing, Frames 7 and 8

A valid analysis using Star's computer program was not possible because the weak axis column slenderness ratio, KL/r, for the unbraced span, exceeded 200. The reason that failure did not occur at the maximum load was that the measured stresses were much lower than the theoretical stresses. Thus, the theoretical moments used as input in the proposed design program were never attained in the test frame.

Good agreement was attained between measured and predicted vertical and sidesway deflections[6]. Lateral deflections were large at the higher loads but proved to be lateral sway of both frames rather than lateral buckling.

Final Test, Full Live Load, Frame 7, with Non-standard Flange Brace Spacings. As in the previous test, a 20 ft. unbraced span was developed in the south rafter as shown in Figure 13. Again an analysis using Star's program was not possible because of the excessive weak axis column slenderness ratio. The frame was subjected to full live load and failed by lateral buckling of the unbraced span at a load of 2.1 kips.

Data given in Table 2 shows excellent agreement between measured and predicted vertical deflections. The maximum lateral deflection was 0.48 in. and the buckled configuration could be clearly seen[6].

Measured brace force, measured at both ends of the unbraced span, gave a maximum brace force of about 0.6 kips. The braces used at these positions were dynamometers calibrated to measure brace force.

Experimentally determined and predicted stresses are shown in Table 2. Excellent agreement was obtained between experimental and predicted stress for the south rafter at the peak. Measured stresses in both the column and rafter at the knee connection were lower than those predicted.

Final Test, Full Live Load, Frame 8. Test results and theoretical predictions from Star Manufacturing Company's design program are shown in Appendix D. The frame failed at an applied load of 3.0 kips at each loading point. This corresponds to a unity check value of 1.70 in Star Manufacturing Company's design program. Failure occurred by lateral buckling of the compression flange of the rafter near the peak. Yielding was visibly more evident on the east side of the flange indicating lateral buckling to the west.

As shown in Figure D.1, excellent agreement was attained between measured and predicted vertical centerline deflections. Failure of the frame is evident from the nonlinearity of the results at the higher load levels. Lateral deflections of the outside and inside flanges are shown in Figures D.2 and D.3, respectively. Careful inspection of Figure D.2 clearly identifies the area of lateral buckling near the peak.

Comparisons between predicted and experimental stresses can be found in Figures D.4, D.5 and D.6. As can be seen in these Figures, experimental stresses were lower than predicted. This is consistent with the full live load test for frame 8 discussed previously.

Results of this test indicate that frame stiffness is adequately predicted by Star Manufacturing Company's design program.

Coupon Tests, Frames 7 and 8. During fabrication of the frame components, samples of the plate material used were taken and machined into standard tensile coupons. The coupons were then tested using standard testing procedures. Measured yield stresses varied from 51.1 to 56.4 ksi. The average measured yield stress was 53.8 ksi.

For the Star Manufacturing Company computer analyses a yield of 50 ksi was used in all cases.

4.2 Comparison of Test Results with Lee's Predictions

In this Section, a few selected test results are compared to critical load predictions found using the Lee procedures discussed previously. For these analyses, only the probable critical sections of the frames were analyzed. In all cases, the critical section as determined by the Lee procedures was in agreement with the critical location as determined through Star Manufacturing Company's design program. For the determination of the major axis effective length factor, K_x, the Star Manufacturing Company's program utilized the approximate method previously discussed. AISC interaction equations D4-1a and D4-1b were used to determine the critical loads. The equivalent moment coefficient, C_m, used in AISC Equation D4-1a, is taken as 0.85 by Lee, however, the Commentary on the AISC Specification[7] suggests that C_m be taken as

$$C_m = 1.0 - 0.18\ f_a/F_e' \qquad (1)$$

for cases where the value of axial stress, f_a, is small. Both values were used for these analyses so that comparisons could be made. Results are summarized in Table 7 where all factors of safety are removed so that an interaction equation value of unity indicates the critical load has been attained.

4.2.1 <u>Frame 1 - SRL04 50 20/25 16/25 - Full Live Load</u>

An analysis of Frame 1 under full live load and using Star Manufacturing Company's standard flange bracing, can be found in Appendix E. The section properties, bending moments, and axial loads used in this analysis were obtained from Star Manufacturing Company's design program (Appendix A). In that analysis the predicted critical load was 5.13 kips at each load location and the critical location was in the rafter section nearest the knee.

An analysis of the frame under the same loading and bracing conditions was completed according to the procedures suggested by Lee <u>et al</u>. as discussed in Chapter 3. Using the Lee analysis, the critical location was found to be in the rafter section nearest the knee which is in agreement with Star Manufacturing Company's design program. Both the interaction equations suggested in Appendix D of the AISC

Table 7
Results of Lee Analyses

Details of Analysis	Lee Analysis				Star Predicted P_{cr}, Kips	Experimental Results
	AISC Eqn. No.	C_m (Eqn. no.)	Unity Check	Predicted P_{cr}, Kips		
Frame 1 - SRLO4 50 20/25 16/25 -Analyzed under full live load = 5.13 kips -Star analysis predicted failure in rafter segment near knee. -Lee analysis predicted failure in rafter segment near knee.	D4-1a	0.85	0.891	5.76	5.13	Frame failed at 4.75 kips by lateral buckling of rafter after failure of flange brace (Fig. 10).
	D4-1a	Eqn. 1	1.034	4.96		
	D4-1b	-	1.001	5.13		
Frame 3 - SR4 60 40/25 20/20 -Nonstandard flange bracing (Fig. 11b). -Analyzed under full live load + 4.5 kips. -Star and Lee analyses predicted failure in rafter near knee.	D4-1a	0.85	0.503 (0.626)	8.95 (7.19)	4.54	Frame failed at 5.76 kips by lateral buckling of rafter near knee.
	D4-1a	Eqn. 1	0.582 (0.723)	7.73 (6.22)		
	D4-1b	-	0.559 (0.680)	8.05 (6.22)		
Frame 6 - STR 60 12/25 10/25 -Analyzed under full live load = 3.98 kips. -Star and Lee analyses predicted failure in rafter near knee.	D4-1a	0.85	0.939	4.24	3.98	Frame failed at 3.0 kips by local buckling of rafter at knee connection. Note: poor erection.
	D4-1a	Eqn. 1	1.082	3.68		
	D4-1b	-	1.055	3.77		
Frame 6 - STR 60 12/25 10/25 -Nonstandard flange bracing (Fig. 12c). -Analyzed under full live load = 3.0 kips -Star analysis unavailable. -Lee analysis predicted failure in 25 ft. unbraced span.	D4-1a	0.85	0.862 (1.50)	3.48 (2.0)	N.A.	Frame failed at 3.0 kips by lateral-torsional buckling of long unbraced span. Note: poor erection.
	D4-1a	Eqn. 1	0.995 (1.73)	3.02 (1.73)		
	D4-1b	-	0.934 (1.60)	3.21 (1.88)		
Frame 7 - STR4 50 12/25 14/25 -Nonstandard flange bracing (Fig. 13b). -Analyzed under full live load = 2.1 kips. -Star analysis unavailable. -Lee analysis predicted failure in 20 ft. unbraced span.	D4-1a	0.85	0.991 (1.66)	2.12 (1.27)	N.A.	Frame failed at 2.1 kips by lateral-torsional buckling of long unbraced span.
	D4-1a	Eqn. 1	1.15 (1.93)	1.83 (1.09)		
	D4-1b	-	1.10 (1.83)	1.91 (1.15)		

Note: ( ) designates that short span between critical span and knee assumed to offer no weak-axis buckling restraint to critical span, ie. one end of critical span is assumed pinned.

N.A. indicates that a Star analysis was not possible because of an excessive rafter slenderness ratio.

Specification were used, as were both values of the equivalent moment coefficient C_m as discussed previously. Results of this analysis are shown in Table 7. The use of 0.85 as the value for C_m in Equation D4-la gave unconservative results (5.76 kips) for this analysis. However, using Equation 1 to determine the value of C_m for use in Equation D4-la gave only slightly unconservative results (4.96 kips) when compared to experimental failure loads (4.75 kips). Equation D4-lb resulted in the same predicted failure load as the Star Manufacturing Company analysis (5.13 kips). Since the experimental failure load was influenced by the failure of a compression flange brace (Figure 10), it could be assumed that the frame would have taken more load had the brace not failed. If this were true, then the critical loads predicted using Equation D4-la with C_m determined by Equation 1 and Equation D4-lb were good predictions of the actual failure load.

4.2.2 Frame 3- SR4 60 40/25 20/20 - Full Live Load

An analysis similar to that discussed above was completed for Frame 3 under full live load with nonstandard flange brace spacings (Figure 11b). The analysis by Star Manufacturing Company resulted in a predicted critical load of 4.54 kips at each loading point with the critical location in the rafter section nearest the knee. The Lee analysis predicted the critical location to be in the rafter but one section away from the knee. Thus in this analysis, the weak-axis buckling restraint given to the critical section by the rafter section nearest the knee had to be considered. Two approaches were used for the estimation of this restraint: (1) The approach presented by Lee <u>et al.</u>[2], i.e., end restraint factors G_T or G_B. And (2) since the adjacent span near the knee was short and near the end of the member, it was assumed it offered no weak-axis buckling restraint and the near end of the critical span was assumed pinned (i.e., G = 10). The results of these analyses can be found in Table 7. The results using the latter method of estimating the end restraint are designated with parenthesis in Table 7.

When tested, the frame failed at a load of 5.76 kips by lateral buckling of the rafter near the knee. The failure location is in agreement with both the Star Manufacturing Company and Lee analysis predictions. However, the failure load was approximately 25 % higher than was predicted by Star Manufacturing Company's (4.54 kips). When AISC Equation D4-1a was used in the Lee analysis, with C_m as defined in Equation 1 and assuming the end of the critical span toward the knee as pinned (i.e., adjacent segment offers no restraint against weak-axis buckling), the predicted critical load was approximately 8% higher than the test result (6.22 kips). All other methods of predicting the critical load using the Lee analysis gave very unconservative results when compared to the test results.

4.2.3 Frame 6 - STR 60 12/25 10/25 - Full Live Load

Star Manufacturing Company Standard Flange Brace Spacings. An analysis of Frame 6 under a full live load of 3.98 kips at each loading point and using Star Manufacturing Company's standard flange bracing was completed using Lee analysis procedures. The results of this analysis are shown in Table 7.

An analysis using Star Manufacturing Company's design program predicted failure in the rafter section nearest the knee at a load of 3.98 kips. The Lee analysis also predicted the critical location in the rafter at the knee. When the frame was tested, it failed at a load of 3.0 kips by local buckling of the rafter at the knee connection. The failure location is in agreement with both the Star Manufacturing Company and Lee analysis procedures. The failure load was much lower than predicted by either of the analysis methods discussed (3.98 kips and 3.68 kips). This can be partially attributed to the poor erection of Frame 6 as discussed previously. Since the low failure load was predicted by poor erection, it is difficult to make comparisons between predictions and test results. Comparisons can be made between the critical loads predicted by the two analysis procedures. The use of AISC Equation D4-la with C_m assumed to be 0.85 resulted in a predicted critical load of 4.24 kips when Lee analysis methods were used. This is approximately 7% higher than Star Manufacturing Company predictions. Using Equation 1 to determine C_m in AISC Equation D4-1a resulted in a critical load of 3.68 kips while using AISC Equation D4-1b predicted the critical load to be 3.77 kips. These values are approximately 8 and 5% lower than Star Manufacturing Company predictions, respectively.

Nonstandard Flange Brace Spacings. An analysis of Frame 6 under a full live load of 3.0 kips with nonstandard flange bracing (Figure 12c) was completed and the results are shown in Table 7. A critical load prediction using Star Manufacturing Company's design program was not possible due to a weak axis rafter slenderness ratio exceeding 200 which is beyond program capabilities. The Lee analysis predicted that failure would occur in the 25 foot unbraced span of the rafter.

When the frame was tested, failure occurred by lateral-torsional buckling of the long unbraced span at a load of 3.0 kips. It is difficult to determine the extent to which the poor erection of the rafter influenced the failure load.

Since the critical location in the Lee analysis was the long unbraced span created by the nonstandard flange bracing used, the weak axis buckling restraint given to the critical span by the short span nearest the knee had to be determined. The two methods discussed in Section 4.2.2 of this report were used. The assumption that the adjacent span offered no buckling restraint (i.e. end of critical span assumed pinned) resulted in critical loads that were much lower than test results (1.88, 1.73 and 2.0 kips). The use of end restraint factors (as suggested by Lee) resulted in critical loads in close agreement with or higher than the test failure load (3.48, 3.02 and 3.21 kips).

4.2.4 Frame 7 - STR4 50 12/25 14/25 - Full Live Load

Frame 7 was analyzed under a full live load of 2.1 kips and with nonstandard flange brace spacings (Figure 13b). A Star Manufacturing Company analysis was unavailable due to the excessive weak-axis rafter slenderness ratio of the long unbraced span. An analysis using the procedures suggested by Lee was completed and the results are shown in Table 7.

When the frame was tested under these conditions, it failed at a load of 2.1 kips by lateral-torsional buckling of the long unbraced span. In analyzing the frame using Lee's methods, predicted critical loads were in good agreement with test results when the weak-axis buckling restraint of the adjacent span near the knee was considered (2.1, 1.83 and 1.91 kips). When this restraint was not considered, the predicted critical loads were very conservative when compared to test results (1.27, 1.09 and 1.15 kips).

CHAPTER V

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

An extensive series of tests of Star Manufacturing Company standard rigid frames has been conducted. The test setups were as close to actual conditions as possible. The frames were subjected to loading combinations commonly used for design. Test results were compared to standard Star Manufacturing Company design procedures and to recently published state-of-art procedures.

5.2 Conclusions

General. From test results it was found that bracing details are extremely critical. Failure of Frame 1 was caused by an inadequate rafter compression flange brace near the knee. The brace failed because of purlin roll which, in turn, occurred because of lack of torsional restriant due to the absence of roof panel. This failure underscores the fact that metal buildings are systems. Caution is recommended if a flange brace is located at an unrestrained purlin, for instance, near a skylight.

The need for adequate bolt tightening is emphasized by the results of tests of Frames 5 and 6. These frames were erected by an outside erection crew, supposedly experienced in metal building erection. The initial test of these frames resulted in premature failure which is believed to have been caused by inadequate tightening of the end-plate moment connection bolts at the knees and peak.

Although not a specific part of this study, it is noted that no failure was attributed to the end-plate connections. In no test, not even those to the failure load, was distress observed in the connections.

Stiffness. All deflection measurements were compared to Star Manufacturing Company's computer design program. The program was found to very accurately predict vertical rafter deflections. Measured sidesway deflections were consistently found to be less than predicted. The program is based on the assumption of perfectly pinned column bases which was not achieved in the test set-up.

Stresses. Measured strains were converted to stress using an assumed modulus of elasticity. Except for tests involving Frames 3 and 4, measured stresses (strains) were less than predicted from the Star Manufacturing Company computer program. Measured stresses (strains) for Frames 7 and 8 were considerably less than predicted. For Frames 3 and 4 good agreement was obtained. No explanation was found for the discrepancy.

Strength. For full live load tests to failure (Table 2), all frames tested reached more than 90% of the predicted failure load except Frames 5 and 6. Calculations were based on a yield stress of 50 ksi except Frames 5 and 6 for which an assumed yield stress of 55 ksi was used. (As noted above Frames 5 and 6 may have been damaged prior to the final test due to inadequate bolt tightening.) Except for Frames 5 and 6 the load factor (failure load/working load) exceeded 1.5. It is the writers' opinion that if the load factor from full scale tests of production specimens exceeds 1.5, the design is adequate.

Only Frames 3 and 4 were tested to failure for other than full live load. These frames were tested to failure using a combination of lateral load and unbalanced live load on the windward side. In this test, gravity live load was first applied and then lateral load. The gravity live load was maintained as the lateral load was applied in increments. The frames failed at 70% of the predicted lateral load failure level (Table 5). However, the stress gradient (versus applied lateral load) was very low near the failure location. The stress at this section was very high upon application of the vertical load (within 19% of the predicted stress at failure) and then increased very slowly with increasing lateral load. Hence, failure at the section at a stress level only slightly below the critical stress can translate into a significant reduction in lateral load capacity. (See Reference 4 for more detailed explanation). It is the writers' opinion that this phenomenon is not adequately addressed by the recognized specifications and codes.

Lee's Procedure. Test results were compared to procedures suggested by Lee *et al.*[2]. A number of variations of design assumptions were investigated (Table 7). No consistent set of design rules which adequately predicted frame strength for all loading combinations was found.

5.3 Recommendations

From this study, it was found that Star Manufacturing Company's design program, as described above, is adequate for the class of frames tested. It is recommended that the program be continued to be used.

It is suggested that procedures be investigated to improve the accuracy of predicted sidesway deflections. From non-standard bracing spacing tests, it was found that the program underestimates the weak axis buckling strength of rafter sections. The assumption of pinned-end segments is obviously conservative and consideration might be given to implementing procedures to include the effects of restraint supplied by adjacent rafter segments, especially near the knee. Finally, a C_b value of 1.0 is used in the program. This assumption can be ultra-conservative for certain conditions. Consideration may be given to implementation of a more accurate estimate of C_b.

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APPENDIX A

DETAILS AND DIMENSIONS OF TEST SPECIMENS

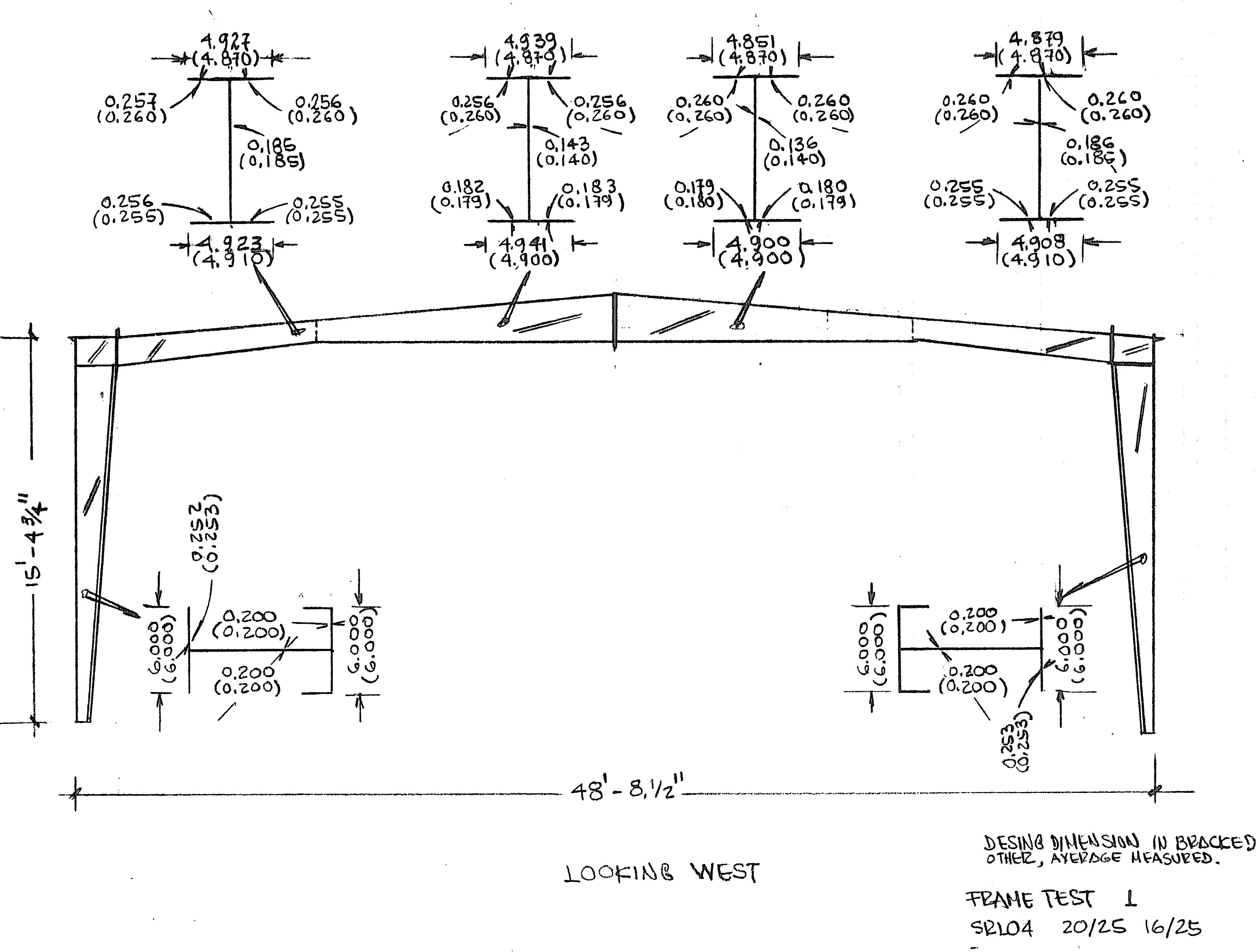


Figure A.1 Details and Dimensions of Test Specimens--Frame 1

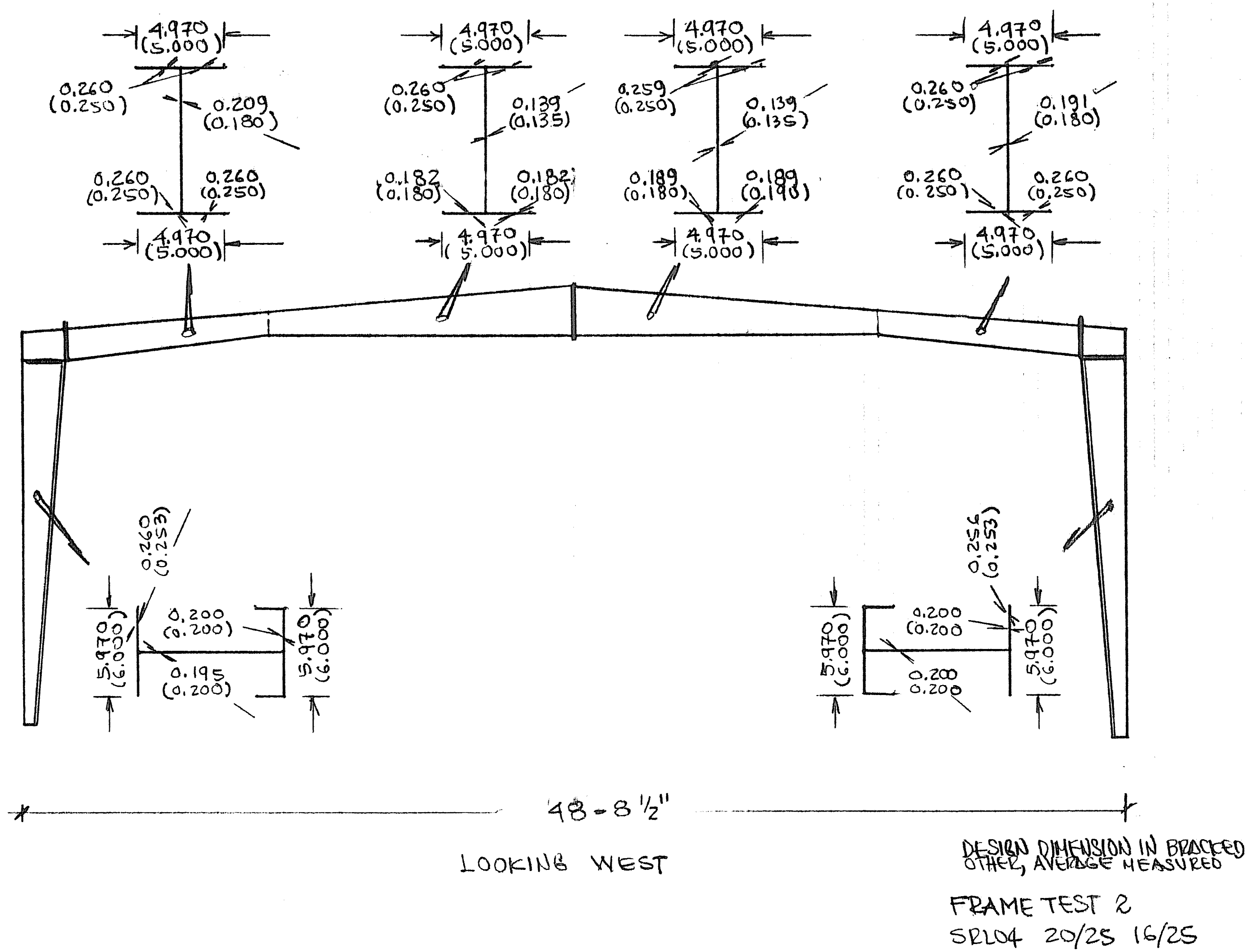


Figure A.2 Details and Dimensions of Test Specimens--Frame 2

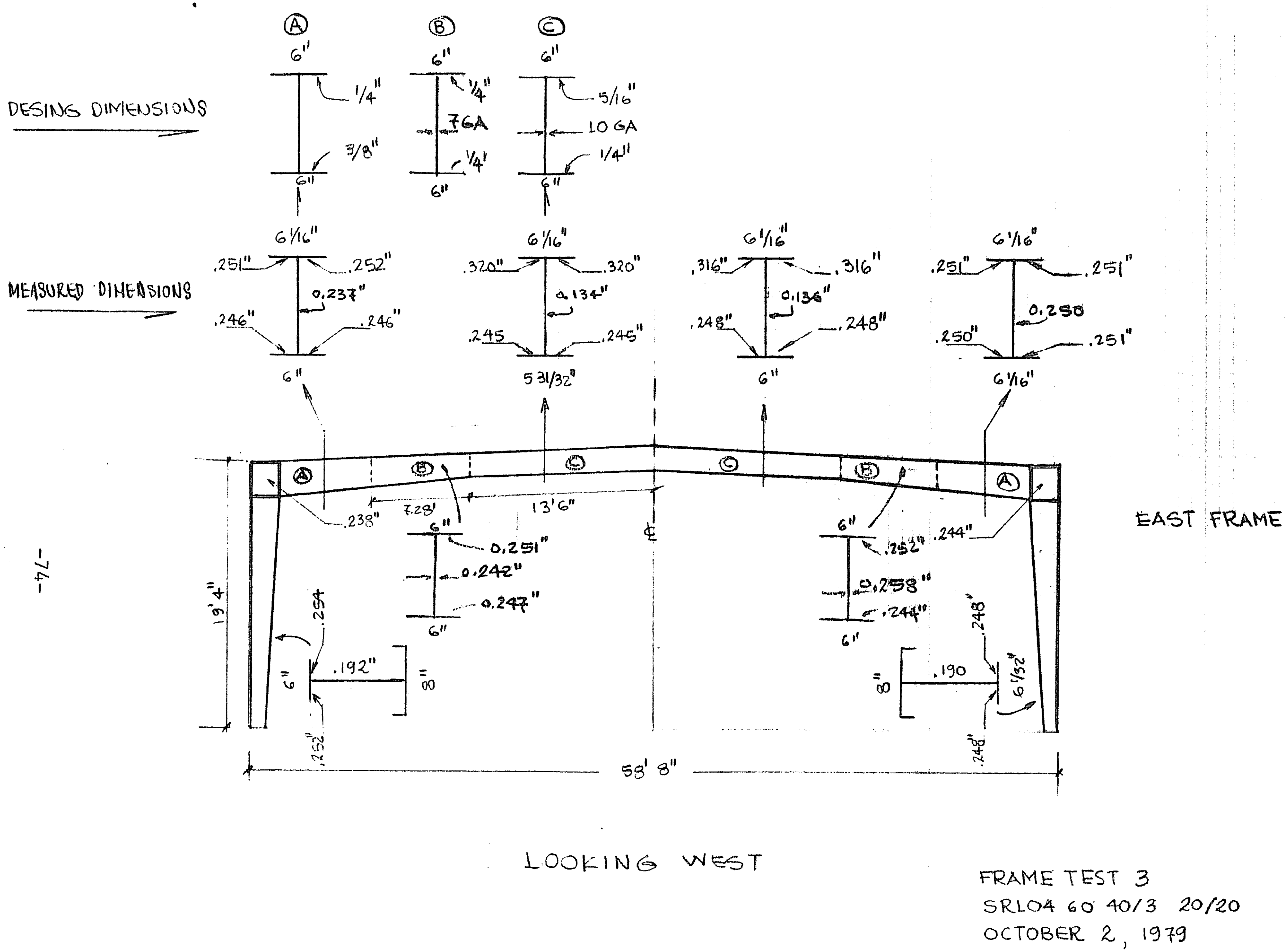


Figure A.3 Details and Dimensions of Test Specimens--Frame 3

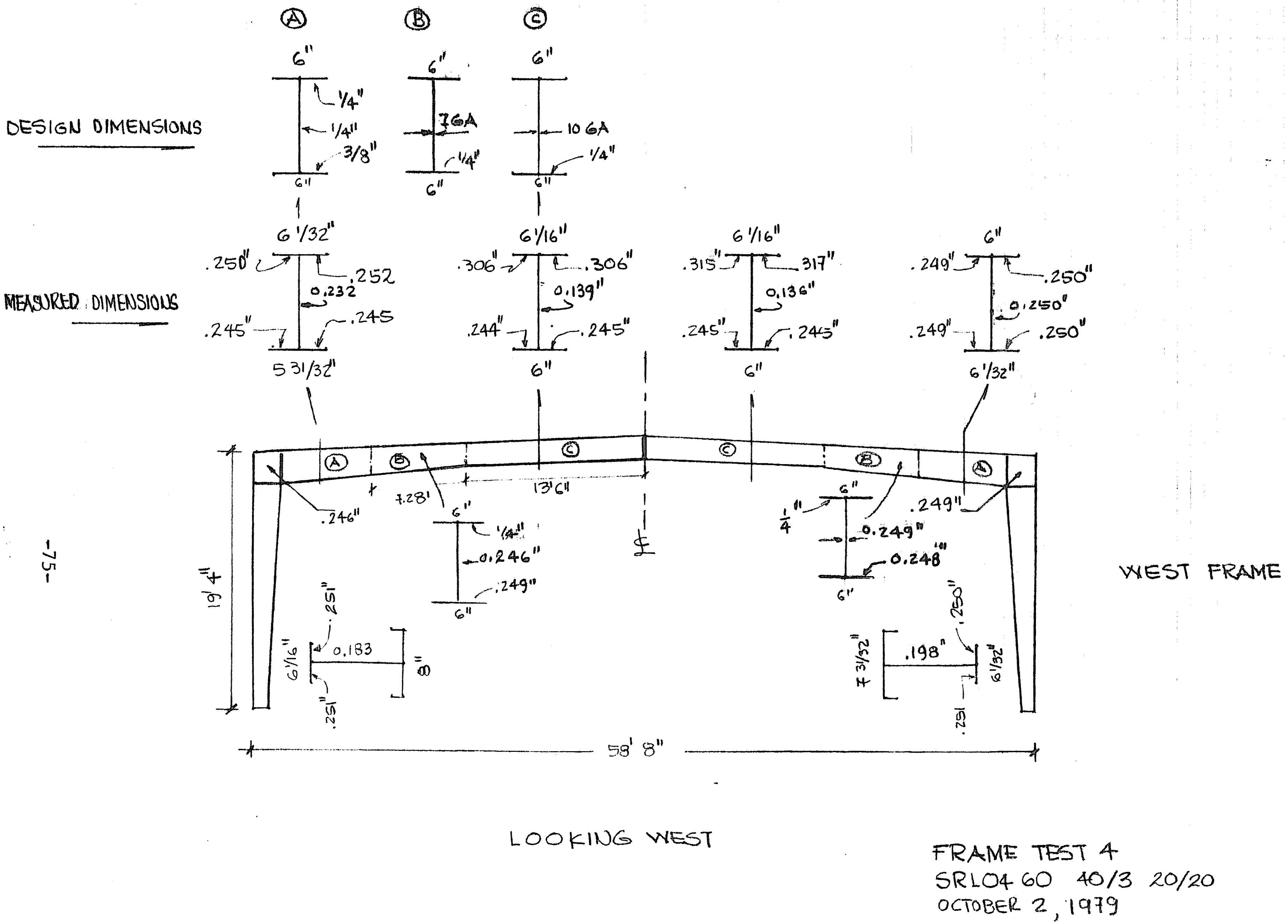
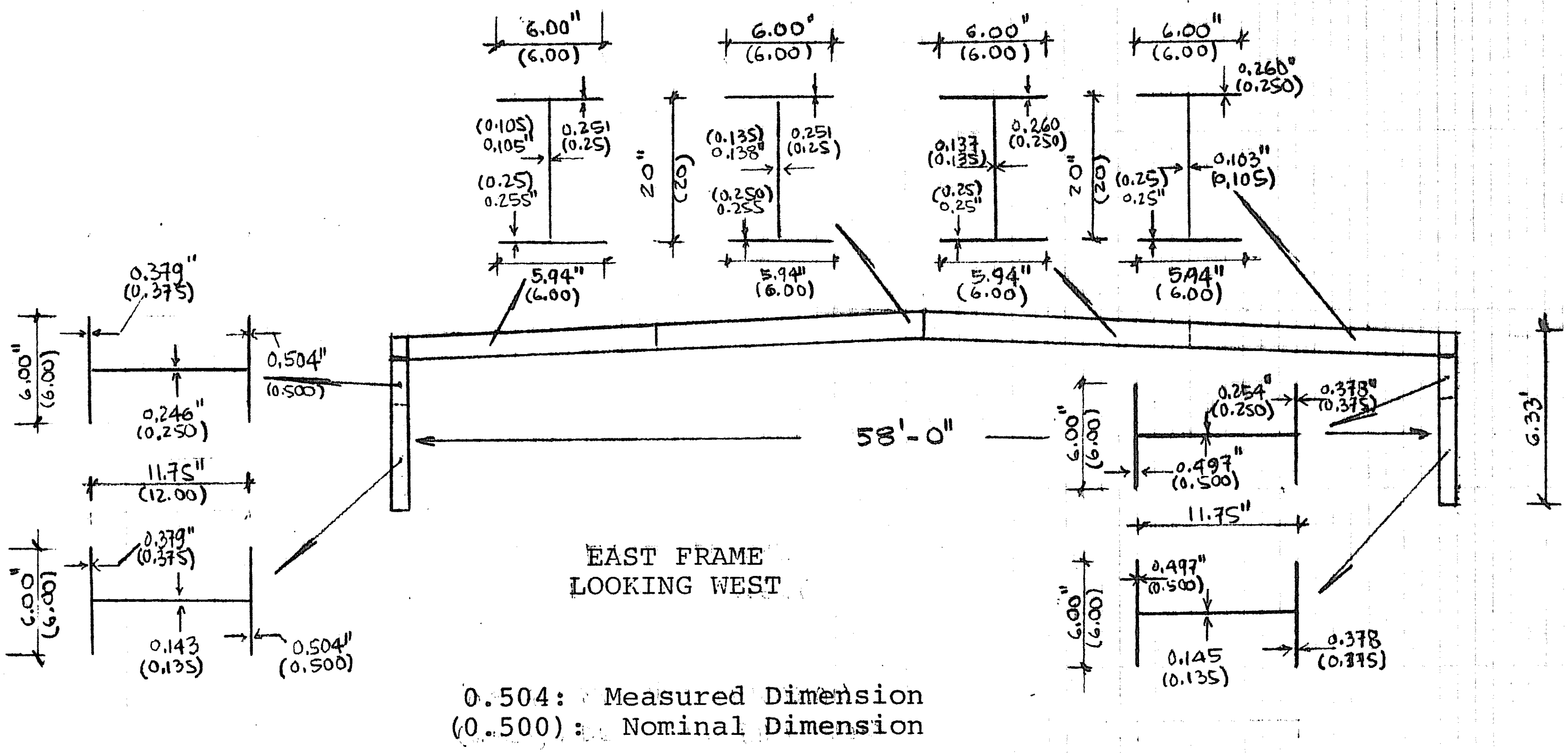


Figure A.4 Details and Dimensions of Test Specimens--Frame 4



FRAME 5
STR 60 12/15 10/25

Figure A.5 Details and Dimensions of Test Specimens--Frame 5

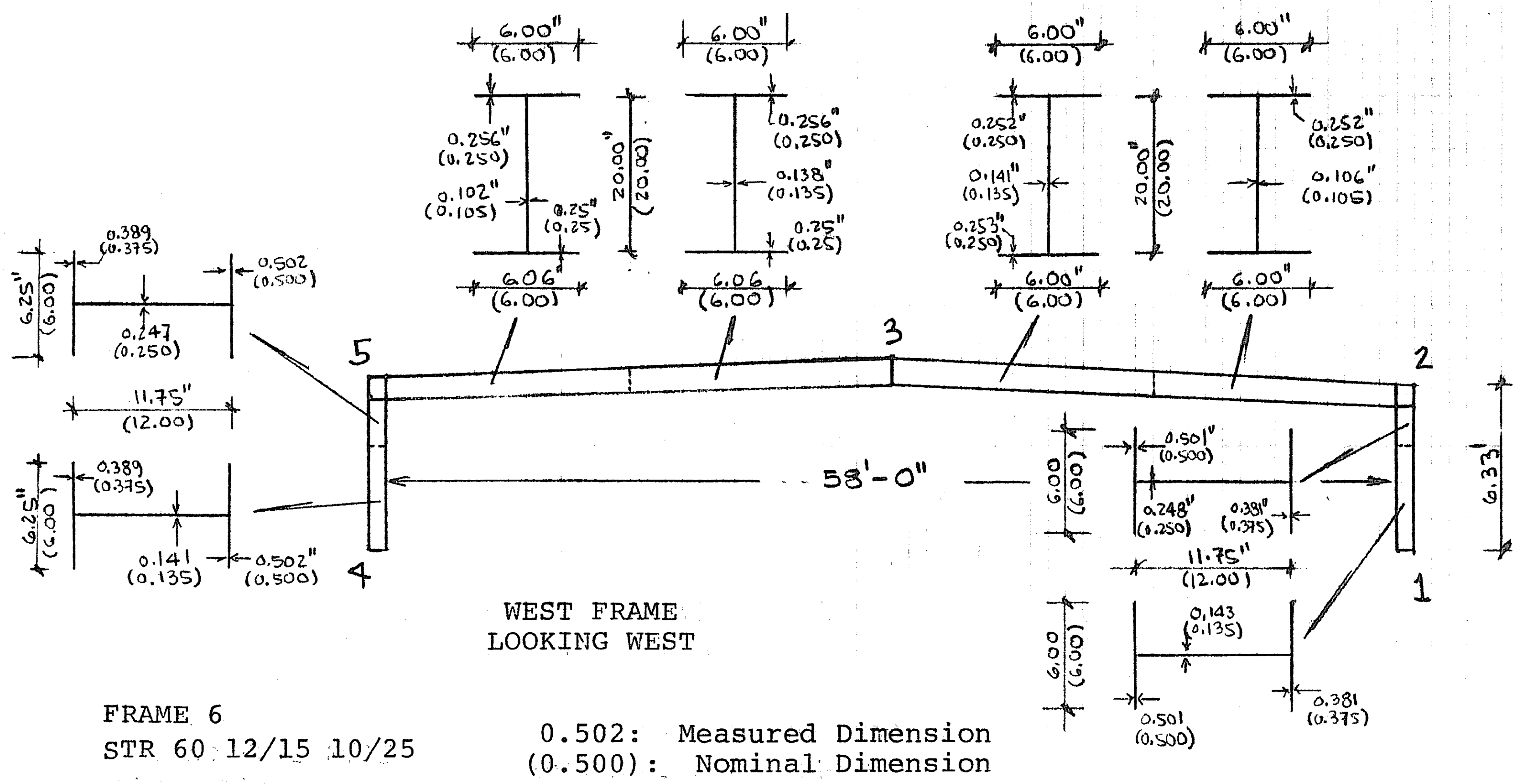
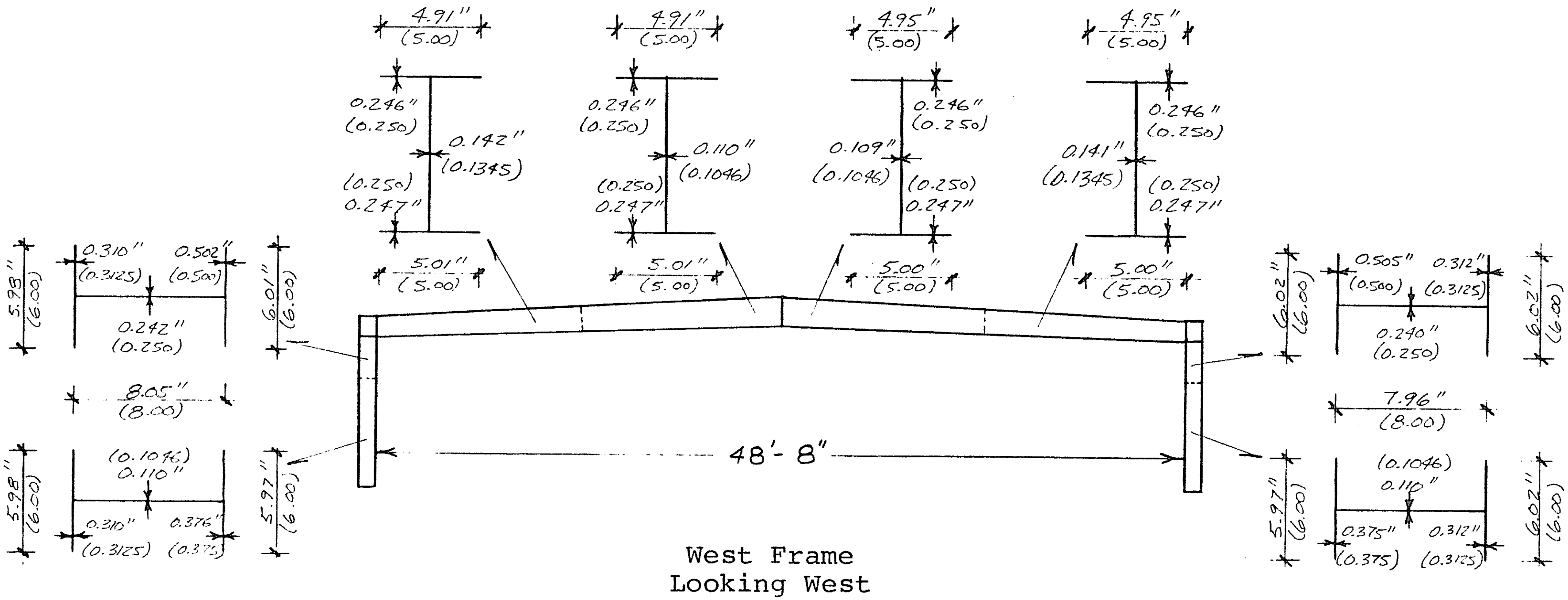


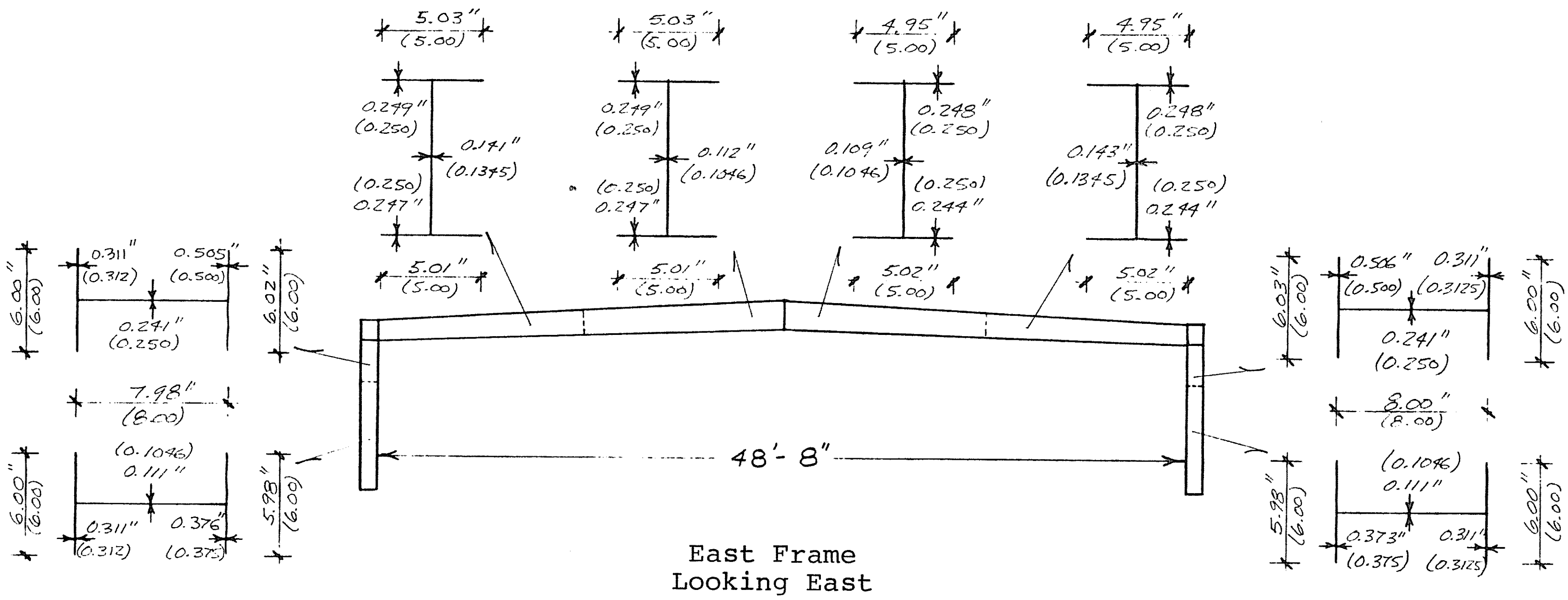
Figure A.6 Details and Dimensions of Test Specimens--Frame 6



Frame 7
STR4 50 12/25 14/25

5.97" : Measured Dimension
(6.00) : Nominal Dimension

Figure A.7 Details and Dimensions of Test Specimens--Frame 7



Frame 8
STR4 50 12/25 14/25

0.373" : Measured Dimension
(0.375) : Nominal Dimension

Figure A.8 Details and Dimensions of Test Specimens --Frame 8

APPENDIX B

TYPICAL STAR MANUFACTURING COMPANY

COMPUTER ANALYSES

(Frames 1 and 2)

STAR MANUFACTURING CO. 8600 S. I-35 OKLAHOMA CITY, OK.
SRL04 50 20/25 16/25
DESIGN DIMENSIONS AND PROPERTIES REPORT

JOB SRLOFRA
FILE OU. FRA. 1
PAGE 3

MEMBER NO. 1- 2 LENGTH= 14.65 FT ANGLE= 87.36 DEG FYF=50. KSI FYW=50. KSI
SECTION 1 LENGTH= 13.87 FT OF= 6.00 X 0.2500 WEB=0.1875 IF=C 6 X 8.2

POINT NO.	X (FT)	Y (FT)	DEPTH (IN)	AREA (IN2)	IX (IN4)	RX (IN)	RY (IN)	SOX (IN3)	SIX (IN3)	RTO (IN)	RTI (IN)
1*	0.00	0.00	6.00	4.94	30.0	2.47	1.89	9.0	11.3	1.630	2.265
101	0.06	1.15	7.22	5.17	45.9	2.98	1.85	11.3	14.4	1.610	2.251
102	0.17	3.46	9.67	5.63	89.1	3.98	1.77	16.4	21.0	1.571	2.222
103	0.28	5.77	12.12	6.09	149.0	4.95	1.70	21.9	28.0	1.536	2.194
104	0.39	8.08	14.57	6.55	226.9	5.89	1.64	27.9	35.3	1.503	2.167
105	0.51	10.39	17.02	7.01	324.3	6.80	1.59	34.3	42.9	1.473	2.140
106	0.62	12.70	19.47	7.47	442.5	7.70	1.54	41.1	50.9	1.444	2.114
107*	0.67	13.86	20.69	7.70	509.9	8.14	1.51	44.6	55.1	1.431	2.102

STAR MANUFACTURING CO. 8600 S. I-35 OKLAHOMA CITY, OK.
SRL04 50 20/25 16/25
DESIGN DIMENSIONS AND PROPERTIES REPORT

JOB SRLOFRA
FILE OU. FRA. 1
PAGE 4

MEMBER NO. 2- 3 LENGTH= 23.47 FT ANGLE= 4.89 DEG FYF=50. KSI FYW=50. KSI
SECTION 1 LENGTH= 7.25 FT OF= 5.00 X 0.2500 WEB=0.1875 IF= 5.00 X 0.2500
SECTION 2 LENGTH= 15.51 FT OF= 5.00 X 0.2500 WEB=0.1345 IF= 5.00 X 0.1799

POINT NO.	X (FT)	Y (FT)	DEPTH (IN)	AREA (IN2)	IX (IN4)	RX (IN)	RY (IN)	SOX (IN3)	SIX (IN3)	RTO (IN)	RTI (IN)
110*	1.38	14.69	20.00	6.16	359.7	7.64	0.92	36.0	36.0	1.184	1.184
111	2.58	14.83	19.00	5.97	318.7	7.31	0.94	33.5	33.5	1.194	1.194
112	4.98	15.13	17.00	5.59	245.6	6.63	0.97	28.9	28.9	1.215	1.215
113	7.38	15.42	15.00	5.22	183.6	5.93	1.00	24.5	24.5	1.237	1.237
114*	8.58	15.56	14.00	5.03	156.6	5.58	1.02	22.4	22.4	1.248	1.248
114*	8.58	15.56	14.00	3.97	128.7	5.69	1.06	20.1	17.0	1.306	1.234
115	10.13	15.67	14.61	4.06	141.9	5.91	1.05	21.1	18.0	1.301	1.227
116	13.22	15.88	15.84	4.22	170.5	6.35	1.03	23.4	20.0	1.290	1.213
117	16.32	16.10	17.07	4.39	202.2	6.79	1.01	25.6	22.0	1.279	1.199
118	19.41	16.31	18.29	4.55	237.3	7.22	0.99	28.0	24.2	1.268	1.187
119	22.51	16.52	19.52	4.72	275.8	7.65	0.97	30.4	26.4	1.258	1.174
3*	24.05	16.63	20.13	4.80	296.4	7.86	0.97	31.6	27.5	1.253	1.168

a) Frame 1

Figure B.1 Geometry and Section Properties

STAR MANUFACTURING CO.   8600 S. I-35   OKLAHOMA CITY, OK.   JOB SRLOFRA
SRL04 50 20/25 16/25   FILE OU. FRA. 1
DESIGN DIMENSIONS AND PROPERTIES REPORT   PAGE 5

MEMBER NO. 3- 5   LENGTH= 23.46 FT   ANGLE= -4.89 DEG   FYF=50. KSI   FYW=50. KSI
SECTION 1   LENGTH= 15.51 FT   OF= 5.00 X 0.2500   WEB=0.1345   IF= 5.00 X 0.1799
SECTION 2   LENGTH= 7.25 FT   OF= 5.00 X 0.2500   WEB=0.1875   IF= 5.00 X 0.2500

POINT NO.	X (FT)	Y (FT)	DEPTH (IN)	AREA (IN2)	IX (IN4)	RX (IN)	RY (IN)	SOX (IN3)	SIX (IN3)	RTO (IN)	RTI (IN)
3*	24.05	16.63	20.19	4.81	298.4	7.88	0.97	31.8	27.6	1.253	1.167
120	25.60	16.52	19.57	4.72	277.6	7.67	0.97	30.5	26.5	1.258	1.174
121	28.70	16.31	18.33	4.56	238.6	7.24	0.99	28.1	24.3	1.268	1.186
122	31.79	16.10	17.10	4.39	203.1	6.80	1.01	25.7	22.1	1.279	1.199
123	34.88	15.88	15.86	4.22	170.9	6.36	1.03	23.4	20.0	1.290	1.213
124	37.98	15.67	14.62	4.06	142.0	5.92	1.05	21.2	18.0	1.301	1.227
125*	39.53	15.56	14.00	3.97	128.7	5.69	1.06	20.1	17.0	1.306	1.234
125*	39.53	15.56	14.00	5.03	156.6	5.58	1.02	22.4	22.4	1.248	1.248
126	40.73	15.42	15.00	5.22	183.6	5.93	1.00	24.5	24.5	1.237	1.237
127	43.13	15.13	17.00	5.59	245.6	6.63	0.97	28.9	28.9	1.215	1.215
128	45.53	14.83	19.00	5.97	318.7	7.31	0.94	33.5	33.5	1.194	1.194
129*	46.73	14.69	20.00	6.16	359.7	7.64	0.92	36.0	36.0	1.184	1.184

STAR MANUFACTURING CO.   8600 S. I-35   OKLAHOMA CITY, OK.   JOB SRLOFRA
SRL04 50 20/25 16/25   FILE OU. FRA. 1
DESIGN DIMENSIONS AND PROPERTIES REPORT   PAGE 6

MEMBER NO. 4- 5   LENGTH= 14.65 FT   ANGLE=-87.35 DEG   FYF=50. KSI   FYW=50. KSI
SECTION 1   LENGTH= 13.87 FT   OF= 6.00 X 0.2500   WEB=0.1875   IF=C 6 X 8.2

POINT NO.	X (FT)	Y (FT)	DEPTH (IN)	AREA (IN2)	IX (IN4)	RX (IN)	RY (IN)	SOX (IN3)	SIX (IN3)	RTO (IN)	RTI (IN)
4*	48.11	0.00	6.00	4.94	30.0	2.47	1.89	9.0	11.3	1.630	2.265
131	48.05	1.15	7.23	5.17	46.0	2.98	1.85	11.4	14.5	1.609	2.251
132	47.94	3.46	9.69	5.63	89.4	3.99	1.77	16.4	21.1	1.571	2.222
133	47.83	5.77	12.15	6.09	149.7	4.96	1.70	22.0	28.0	1.535	2.194
134	47.71	8.08	14.60	6.55	228.1	5.90	1.64	28.0	35.4	1.502	2.167
135	47.60	10.39	17.06	7.01	326.2	6.82	1.58	34.4	43.1	1.472	2.140
136	47.49	12.70	19.52	7.48	445.4	7.72	1.53	41.2	51.1	1.444	2.114
137*	47.43	13.86	20.75	7.71	513.3	8.16	1.51	44.8	55.3	1.430	2.101

a) Frame 1 Continued

Figure B.1 Geometry and Section Properties Continued

STAR MANUFACTURING CO. 8600 S. I-35 OKLAHOMA CITY, OK. JOB SRLOFRA
SRL04 50 20/25 16/25 FILE TEST.TMP.3
DESIGN DIMENSIONS AND PROPERTIES REPORT PAGE 3

MEMBER NO. 1- 2 LENGTH= 14.65 FT ANGLE= 87.33 DEG FYF=50.KSI FYW=50.KSI
SECTION 1 LENGTH= 13.88 FT OF= 5.97 X 0.2600 WEB=0.1950 IF=C 6 X 8.2

POINT NO	X (FT)	Y (FT)	DEPTH (IN)	AREA (IN2)	IX (IN4)	RX (IN)	RY (IN)	SOX (IN3)	SIX (IN3)	RTO (IN)	RTI (IN)
1*	0.00	0.00	6.00	5.03	30.6	2.47	1.88	9.3	11.4	1.623	2.261
101	0.06	1.15	7.25	5.28	47.2	2.99	1.83	11.7	14.6	1.602	2.246
102	0.17	3.46	9.75	5.76	92.6	4.01	1.75	17.1	21.4	1.563	2.216
103	0.28	5.77	12.25	6.25	155.9	4.99	1.68	22.9	28.6	1.527	2.186
104	0.40	8.08	14.75	6.74	238.5	5.95	1.62	29.2	36.2	1.494	2.157
105	0.51	10.39	17.25	7.23	342.0	6.88	1.57	36.0	44.2	1.463	2.129
106	0.63	12.70	19.75	7.71	467.9	7.79	1.52	43.2	52.5	1.435	2.102
107*	0.68	13.86	21.00	7.96	539.8	8.24	1.49	46.9	56.9	1.421	2.088

STAR MANUFACTURING CO. 8600 S. I-35 OKLAHOMA CITY, OK. JOB SRLOFRA
SRL04 50 20/25 16/25 FILE TEST.TMP.3
DESIGN DIMENSIONS AND PROPERTIES REPORT PAGE 4

MEMBER NO. 2- 3 LENGTH= 23.46 FT ANGLE= 4.88 DEG FYF=50.KSI FYW=50.KSI
SECTION 1 LENGTH= 7.25 FT OF= 4.97 X 0.2600 WEB=0.2090 IF= 4.97 X 0.2600
SECTION 2 LENGTH= 15.48 FT OF= 4.97 X 0.2540 WEB=0.1930 IF= 4.97 X 0.1840

POINT NO.	X (FT)	Y (FT)	DEPTH (IN)	AREA (IN2)	IX (IN4)	RX (IN)	RY (IN)	SOX (IN3)	SIX (IN3)	RTO (IN)	RTI (IN)
110*	1.41	14.69	20.00	6.66	380.5	7.56	0.90	38.1	38.1	1.162	1.162
111	2.61	14.84	19.00	6.45	336.8	7.23	0.91	35.5	35.5	1.173	1.173
112	5.01	15.13	17.00	6.03	259.0	6.55	0.94	30.5	30.5	1.194	1.194
113	7.41	15.42	15.00	5.61	193.3	5.87	0.97	25.8	25.8	1.217	1.217
114*	8.61	15.56	14.00	5.40	164.7	5.52	0.99	23.5	23.5	1.229	1.229
114*	8.61	15.56	14.00	4.79	142.3	5.45	0.97	21.8	19.0	1.249	1.167
115	10.15	15.67	14.60	4.91	157.0	5.65	0.96	23.0	20.2	1.242	1.159
116	13.24	15.83	15.80	5.14	189.1	6.06	0.93	25.5	22.5	1.229	1.143
117	16.33	16.09	17.00	5.37	224.8	6.47	0.91	28.2	24.9	1.216	1.127
118	19.42	16.31	18.20	5.60	264.4	6.87	0.90	30.9	27.5	1.203	1.113
119	22.51	16.52	19.40	5.84	308.1	7.27	0.88	33.6	30.1	1.190	1.078
3*	24.06	16.62	20.00	5.95	331.4	7.46	0.87	35.1	31.4	1.184	1.092

b) Frame 2

Figure B.1 Geometry and Section Properties Continued

STAR MANUFACTURING CO. 8600 S. I-35 OKLAHOMA CITY, OK. JOB SRLOFRA
SRL04 50 20/25 16/25 FILE TEST. TMP. 3
DESIGN DIMENSIONS AND PROPERTIES REPORT PAGE 5

MEMBER NO 3- 5 LENGTH= 23. 46 FT ANGLE= -4. 87 DEG FYF=50. KSI FYW=50. KSI
SECTION 1 LENGTH= 15. 48 FT OF= 4. 97 X 0. 2540 WEB=0. 1870 IF= 4. 97 X 0. 1840
SECTION 2 LENGTH= 7. 25 FT OF= 4. 97 X 0. 2570 WEB=0. 1910 IF= 4. 97 X 0. 2550

POINT NO.	X (FT)	Y (FT)	DEPTH (IN)	AREA (IN2)	IX (IN4)	RX (IN)	RY (IN)	SOX (IN3)	SIX (IN3)	RTO (IN)	RTI (IN)
3*	24. 06	16. 62	20. 00	5. 83	327. 7	7. 49	0. 88	34. 7	31. 0	1. 190	1. 099
120	25. 60	16. 52	19. 40	5. 72	304. 6	7. 30	0. 89	33. 3	29. 7	1. 196	1. 105
121	28. 69	16. 31	18. 20	5. 50	261. 6	6. 90	0. 90	30. 6	27. 1	1. 209	1. 119
122	31. 78	16. 09	17. 00	5. 27	222. 5	6. 50	0. 92	27. 9	24. 7	1. 221	1. 134
123	34. 87	15. 88	15. 80	5. 05	187. 2	6. 09	0. 94	25. 3	22. 3	1. 234	1. 149
124	37. 96	15. 67	14. 60	4. 83	155. 6	5. 68	0. 96	22. 8	20. 0	1. 247	1. 165
125*	39. 51	15. 56	14. 00	4. 71	141. 1	5. 47	0. 98	21. 6	18. 9	1. 254	1. 173
125*	39. 51	15. 56	14. 00	5. 12	159. 2	5. 58	1. 01	22. 8	22. 7	1. 242	1. 240
126	40. 71	15. 42	15. 00	5. 31	186. 7	5. 93	0. 99	24. 9	24. 9	1. 230	1. 229
127	43. 11	15. 13	17. 00	5. 69	249. 7	6. 62	0. 96	29. 4	29. 3	1. 209	1. 207
128	45. 51	14. 84	19. 00	6. 08	324. 1	7. 30	0. 93	34. 2	34. 1	1. 188	1. 186
129*	46. 71	14. 69	20. 00	6. 27	365. 8	7. 64	0. 92	36. 6	36. 5	1. 178	1. 176

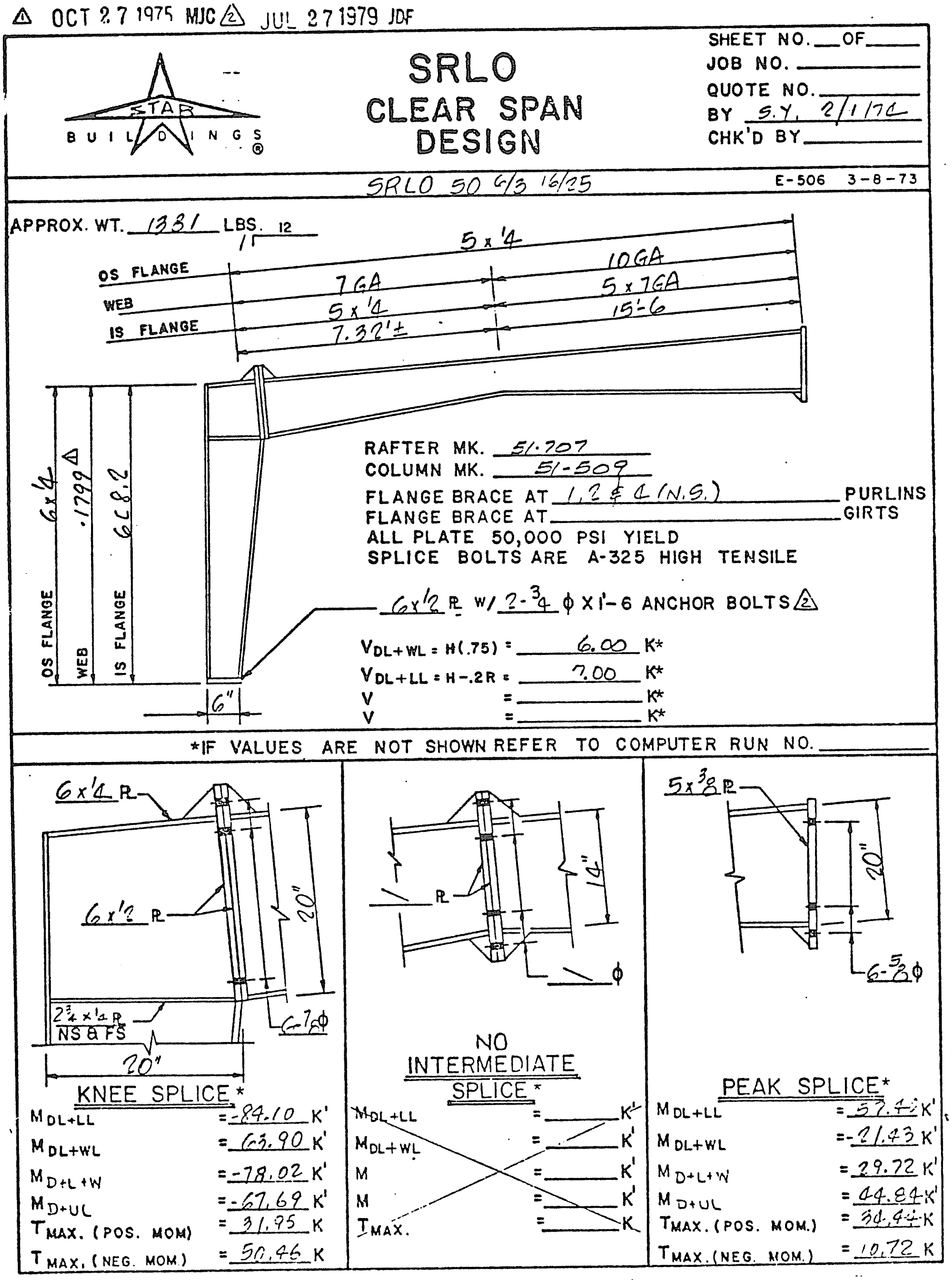
STAR MANUFACTURING CO. 8600 S. I-35 OKLAHOMA CITY, OK. JOB SRLOFRA
SRL04 50 20/25 16/25 FILE TEST. TMP. 3
DESIGN DIMENSIONS AND PROPERTIES REPORT PAGE 6

MEMBER NO. 4- 5 LENGTH= 14. 65 FT ANGLE=-87. 32 DEG FYF=50. KSI FYW=50. KSI
SECTION 1 LENGTH= 13. 88 FT OF= 5. 97 X 0. 2560 WEB=0. 1970 IF=C 6 X 8. 2

POINT NO.	X (FT)	Y (FT)	DEPTH (IN)	AREA (IN2)	IX (IN4)	RX (IN)	RY (IN)	SOX (IN3)	SIX (IN3)	RTO (IN)	RTI (IN)
4*	48. 11	0. 00	6. 00	5. 02	30. 4	2. 46	1. 87	9. 2	11. 4	1. 620	2. 261
131	48. 06	1. 15	7. 25	5. 27	46. 9	2. 98	1. 83	11. 6	14. 6	1. 599	2. 246
132	47. 94	3. 46	9. 75	5. 76	92. 2	4. 00	1. 75	16. 9	21. 4	1. 559	2. 215
133	47. 83	5. 77	12. 25	6. 25	155. 2	4. 98	1. 68	22. 7	28. 6	1. 522	2. 185
134	47. 72	8. 08	14. 75	6. 74	237. 5	5. 93	1. 62	29. 0	36. 2	1. 489	2. 156
135	47. 60	10. 39	17. 25	7. 24	340. 8	6. 86	1. 56	35. 7	44. 2	1. 458	2. 128
136	47. 49	12. 70	19. 75	7. 73	466. 6	7. 77	1. 51	42. 9	52. 5	1. 429	2. 100
137*	47. 43	13. 86	21. 00	7. 98	538. 4	8. 22	1. 49	46. 7	56. 9	1. 415	2. 087

b) Frame 2 Continued

Figure B.1 Geometry and Section Properties Continued

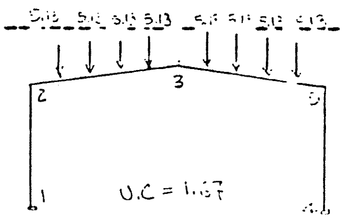


c) Nominal Dimensions - Frames 1 and 2

Figure B.1 Geometry and Section Properties Continued

STAR MANUFACTURING CO.   8600 S. I-35   OKLAHOMA CITY, OK.   JOB SRLOFRA
SRL04 50 20/25 16/25   FILE OU.FRA.1
FORCE, MOMENT, AND STRESS REPORT   PAGE 15
MEMBER 1 - 2   LOAD CONDITION 3 - P=5.13 KIPS   U.C.=1.67

POINT NO.	AXIAL FORCE (KIP)	MOMENT (KIP-FT)	SHEAR FORCE (KIP)	-ALLOWABLE STRESS- FA (KSI)	FBO (KSI)	FBI (KSI)	ALLOW SHEAR (KIP)	A/H RATIO	-UNITY CHECK- UCA	BEND (CF)	BEND (IF)	MAX. COMB UC	DEFLECTIONS DELTA-X (IN)	DELTA-Y (IN)
1*	21.06	0.0	-10.61	13.07	14.61	30.00	20.81	NONE	0.33	0.00	0.00	0.33	0.0000	0.0000
101	21.06	-12.3	-10.61	15.77	30.00	23.36	25.40	NONE	0.26	0.43	0.47	0.73	-0.1938	0.0070
102	21.06	-36.8	-10.61	14.83	30.00	23.10	34.58	NONE	0.25	0.90	0.87	1.12	-0.5118	0.0179
103	21.06	-61.3	-10.61	13.91	30.00	22.84	37.77	NONE	0.25	1.12	1.05	1.30	-0.7041	0.0233
104	21.06	-85.9	-10.61	12.98	30.00	22.57	37.77	NONE	0.25	1.23	1.15	1.40	-0.7667	0.0230
105	21.06	-110.4	-10.61	12.14	30.00	22.30	33.08	NONE	0.25	1.29	1.21	1.46	-0.7090	0.0174
106	21.06	-135.0	-10.61	11.39	30.00	22.03	28.82	NONE	0.25	1.31	1.25	1.50	-0.5429	0.0069
107*	21.06	-147.2	-10.61	11.05	30.00	21.89	27.08	NONE	0.25	1.32	1.27	1.52	------	------



STAR MANUFACTURING CO.   8600 S. I-35   OKLAHOMA CITY, OK.   JOB SRLOFRA
SRL04 50 20/25 16/25   FILE OU.FRA.1
FORCE, MOMENT, AND STRESS REPORT   PAGE 16
MEMBER 2 - 3   LOAD CONDITION 3 - P=5.13 KIPS   U.C.=1.67

POINT NO.	AXIAL FORCE (KIP)	MOMENT (KIP-FT)	SHEAR FORCE (KIP)	-ALLOWABLE STRESS- FA (KSI)	FBO (KSI)	FBI (KSI)	ALLOW SHEAR (KIP)	A/H RATIO	-UNITY CHECK- UCA	BEND (CF)	BEND (IF)	MAX. COMB UC	DEFLECTIONS DELTA-X (IN)	DELTA-Y (IN)
110*	14.01	-142.5	18.97	26.27	30.00	30.00	28.11	NONE	0.09	1.58	1.58	1.67	------	------
111	14.01	-119.5	18.97	26.04	30.00	30.00	29.63	NONE	0.09	1.43	1.43	1.52	-0.3071	-0.2819
112	14.01	-73.7	18.97	22.31	30.00	29.32	33.22	NONE	0.11	1.02	1.04	1.16	-0.2676	-0.7456
113	13.39	-32.0	13.88	22.68	30.00	29.46	37.77	NONE	0.11	0.52	0.53	0.65	-0.2235	-1.3112
114*	13.39	-15.2	13.88	10.67	30.00	18.12	37.77	NONE	0.25	0.27	0.40	0.65	------	------
114*	12.65	-15.2	14.55	11.61	30.00	17.76	14.91	NONE	0.27	0.30	0.54	0.82	------	------
115	12.65	7.3	14.55	11.37	29.83	30.00	14.26	NONE	0.27	0.12	0.16	0.40	-0.1660	-2.0209
116	12.30	43.9	9.44	10.93	29.77	30.00	13.13	NONE	0.27	0.67	0.89	0.94	-0.1044	-2.7873
117	12.30	73.2	9.44	10.52	29.71	30.00	12.16	NONE	0.27	1.01	1.33	1.28	-0.0546	-3.4136
118	11.95	87.8	4.32	19.20	29.65	30.00	11.33	NONE	0.14	1.27	1.45	1.41	-0.0217	-3.8398
119	11.60	96.4	-0.80	18.79	29.52	30.00	10.60	NONE	0.13	1.29	1.46	1.42	-0.0067	-4.0567
3*	11.60	95.1	-0.80	18.53	29.75	30.00	10.27	NONE	0.13	1.21	1.38	1.34	-0.0056	-4.0695

Figure B.2 Stress and Deflection Data, Full Live Load, Frame 1

STAR MANUFACTURING CO. 8600 S. I-35 OKLAHOMA CITY, OK. JOB SRLOFRA
SRLO4 50 20/25 16/25 FILE OU. FRA. 1
FORCE, MOMENT, AND STRESS REPORT PAGE 17
MEMBER 3 - 5 LOAD CONDITION 3 - P=5.13 KIPS U.C.=1.67

POINT NO.	AXIAL FORCE (KIP)	MOMENT (KIP-FT)	SHEAR FORCE (KIP)	-ALLOWABLE STRESS- FA (KSI)	FBO (KSI)	FBI (KSI)	ALLOW SHEAR (KIP)	A/H RATIO	-UNITY CHECK- UCA	BEND (OF)	BEND (IF)	MAX. COMB UC	DEFLECTIONS DELTA-X (IN)	DELTA-Y (IN)
3*	11.60	95.1	0.80	18.53	29.74	30.00	10.24	NONE	0.13	1.21	1.38	1.34	-0.0056	-4.0895
120	11.60	96.4	0.80	18.77	29.51	30.00	10.57	NONE	0.13	1.28	1.45	1.41	-0.0044	-4.0555
121	11.95	87.9	-4.32	19.19	29.65	30.00	11.30	NONE	0.14	1.27	1.45	1.40	0.0108	-3.8373
122	12.30	73.2	-9.44	10.51	29.71	30.00	12.14	NONE	0.27	1.01	1.33	1.28	0.0436	-3.4109
123	12.30	44.0	-9.44	10.92	29.77	30.00	13.11	NONE	0.27	0.67	0.88	0.94	0.0934	-2.7853
124	12.65	7.4	-14.55	11.37	29.83	30.00	14.26	NONE	0.27	0.13	0.16	0.40	0.1550	-2.0201
125*	12.65	-15.2	-14.55	11.61	30.00	17.76	14.91	NONE	0.27	0.30	0.54	0.82	------	------
125*	13.39	-15.2	-13.88	10.67	30.00	18.12	37.77	NONE	0.25	0.27	0.40	0.65	------	------
126	13.39	-31.9	-13.88	22.68	30.00	29.46	37.77	NONE	0.11	0.52	0.53	0.64	0.2124	-1.3111
127	14.01	-73.6	-18.97	22.31	30.00	29.32	33.22	NONE	0.11	1.02	1.04	1.15	0.2594	-0.7459
128	14.01	-119.4	-18.97	26.04	30.00	30.00	29.63	NONE	0.09	1.42	1.42	1.51	0.2959	-0.2825
129*	14.01	-142.4	-18.97	26.27	30.00	30.00	28.11	NONE	0.09	1.58	1.58	1.67	------	------

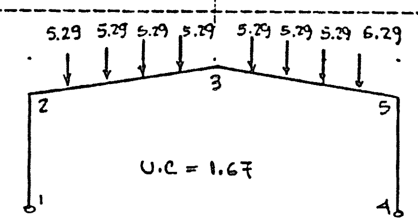
STAR MANUFACTURING CO. 8600 S. I-35 OKLAHOMA CITY, OK. JOB SRLOFRA
SRLO4 50 20/25 16/25 FILE OU. FRA. 1
FORCE, MOMENT, AND STRESS REPORT PAGE 18
MEMBER 4 - 5 LOAD CONDITION 3 - P=5.13 KIPS U.C.=1.67

POINT NO.	AXIAL FORCE (KIP)	MOMENT (KIP-FT)	SHEAR FORCE (KIP)	-ALLOWABLE STRESS- FA (KSI)	FBO (KSI)	FBI (KSI)	ALLOW SHEAR (KIP)	A/H RATIO	-UNITY CHECK- UCA	BEND (OF)	BEND (IF)	MAX. COMB UC	DEFLECTIONS DELTA-X (IN)	DELTA-Y (IN)
4*	21.06	0.0	10.61	13.07	14.61	30.00	20.81	NONE	0.33	0.00	0.00	0.33	0.0000	0.0000
131	21.06	-12.3	10.61	15.77	30.00	23.36	25.42	NONE	0.26	0.43	0.47	0.73	0.1922	0.0069
132	21.06	-36.8	10.61	14.83	30.00	23.10	34.64	NONE	0.25	0.90	0.87	1.12	0.5070	0.0178
133	21.06	-61.3	10.61	13.90	30.00	22.84	37.77	NONE	0.25	1.12	1.05	1.29	0.6968	0.0231
134	21.06	-85.9	10.61	12.97	30.00	22.57	37.77	NONE	0.25	1.23	1.15	1.39	0.7574	0.0227
135	21.06	-110.4	10.61	12.12	30.00	22.30	32.99	NONE	0.25	1.28	1.21	1.46	0.6934	0.0170
136	21.06	-134.9	10.61	11.37	30.00	22.02	28.74	NONE	0.25	1.31	1.25	1.50	0.5317	0.0065
137*	21.06	-147.2	10.61	11.03	30.00	21.89	27.00	NONE	0.25	1.31	1.27	1.51	------	------

Figure B.2 Stress and Deflection Data, Full Live Load, Frame 1 Continued

STAR MANUFACTURING CO.   E600 S   I-35   OKLAHOMA CITY, OK   JOB   SRLOFRA
[illegible]   FILE   TEST.TMP.3
FORCE, MOMENT, AND STRESS REPORT   PAGE   19
MEMBER 1 - 2   LOAD CONDITION 4 - P=5.29 KIPS   U.C.=1.67

POINT NO	AXIAL FORCE (KIP)	MOMENT (KIP-FT)	SHEAR FORCE (KIP)	-ALLOWABLE STRESS- FA (KSI)	FBO (KSI)	FBI (KSI)	ALLOW SHEAR (KIP)	A/H RATIO	-UNITY CHECK- UCA	BEND (OF)	BEND (IF)	MAX. COMB UC	DEFLECTIONS DELTA-X (IN)	DELTA-Y (IN)
1*	21.70	0.0	-10.79	13.08	14.48	30.00	21.61	NONE	0.33	0.00	0.00	0.33	0.0000	0.0000
101	21.70	-12.5	-10.79	15.62	30.00	23.31	26.48	NONE	0.26	0.43	0.48	0.74	-0.1861	0.0067
102	21.70	-37.4	-10.79	14.63	30.00	23.04	36.33	NONE	0.26	0.88	0.87	1.13	-0.4895	0.0171
103	21.[illegible]	-[illegible].4	-10.79	13.65	30.00	22.76	40.85	NONE	0.25	1.09	1.04	1.30	-0.6700	0.0221
104	21.[illegible]	-87.3	-10.79	12.69	30.00	22.47	40.85	NONE	0.25	1.20	1.14	1.40	-0.7242	0.0214
105	21.[illegible]	-112.[illegible]	-10.79	11.84	30.00	22.18	36.72	NONE	0.25	1.25	1.20	1.46	-0.6620	0.0155
106	21.70	-137.2	-10.79	11.69	30.00	21.89	31.96	NONE	0.25	1.27	1.24	1.50	-0.4952	0.0050
107*	21.70	-149.7	-10.79	10.75	30.00	21.74	30.02	NONE	0.25	1.28	1.26	1.51	------	------



STAR MANUFACTURING CO.   E600 S. I-35   OKLAHOMA CITY, OK.   JOB   SRLOFRA
[illegible] 50 20/25 16/25   FILE   TEST.TMP.3
FORCE, MOMENT, AND STRESS REPORT   PAGE   20
MEMBER 2 - 3   LOAD CONDITION 4 - P=5.29 KIPS   U.C.=1.67

POINT NO	AXIAL FORCE (KIP)	MOMENT (KIP-FT)	SHEAR FORCE (KIP)	-ALLOWABLE STRESS- FA (KSI)	FBO (KSI)	FBI (KSI)	ALLOW SHEAR (KIP)	A/H RATIO	-UNITY CHECK- UCA	BEND (OF)	BEND (IF)	MAX. COMB UC	DEFLECTIONS DELTA-X (IN)	DELTA-Y (IN)
110*	14.30	-144.3	19.56	26.21	30.00	30.00	38.97	NONE	0.08	1.32	1.52	1.60	------	------
111	14.[illegible]	-120.6	19.55	25.[illegible]8	30.00	30.00	41.08	NONE	0.09	1.36	1.36	1.45	-0.2619	-0.2827
112	14.30	-73.3	19.56	22.02	30.00	29.18	46.06	NONE	0.11	0.96	0.99	1.10	-0.2253	-0.7365
113*	13.[illegible]6	-3[illegible]	14.[illegible]	22.41	30.00	27.33	46.92	NONE	0.11	0.47	0.48	0.59	-0.1806	-1.2864
114*	13.66	-13.2	14.32	10.16	30.00	17.65	46.92	NONE	0.25	0.22	0.34	0.59	------	------
114*	12.90	-13.2	15.00	9.64	30.00	15.96	40.02	NONE	0.28	0.24	0.46	0.74	------	------
115	12.90	10.1	15.00	9.41	29.49	30.00	40.02	NONE	0.28	0.16	0.20	0.44	-0.1250	-1.9708
116	12.51	47.6	9.73	8.99	29.41	30.00	38.91	NONE	0.27	0.67	0.85	0.94	-0.0658	-2.7027
117	12.54	77.8	9.73	8.60	29.32	30.00	36.09	NONE	0.27	0.99	1.25	1.26	-0.0182	-3.2978
118	12.18	92.8	4.46	18.16	29.24	30.00	33.65	NONE	0.12	1.23	1.35	1.35	0.0133	-3.7023
119	11.62	101.5	-0.81	17.81	29.15	30.00	31.52	NONE	0.11	1.24	1.35	1.36	0.0280	-3.9089
3*	11.[illegible]	10[illegible].3	-0.81	17.60	30.00	30.00	30.56	NONE	0.11	1.14	1.28	1.26	0.0294	-3.9410

Figure B.3 Stress and Deflection Data, Full Live Load, Frame 2

[illegible] CO. 6600 S. I-35 OKLAHOMA CITY, OK. JOB SRLOFRA
[illegible] FILE TEST. TMP. 3
[illegible] MOMENT AND STRESS REPORT PAGE 21
[illegible] LOAD CONDITION 4 - P=5.29 KIPS U.C.=1.67

POINT ID	AXIAL FORCE (KIP)	MOMENT (KIP-FT)	SHEAR FORCE (KIP)	-ALLOWABLE STRESS- FA (KSI)	FBO (KSI)	FBI (KSI)	ALLOW SHEAR (KIP)	A/H RATIO	-UNITY CHECK- UCA	BEND (OF)	BEND (IF)	MAX. COMB UC	DEFLECTIONS DELTA-X (IN)	DELTA-Y (IN)
3*	11.92	100.3	0.81	17.81	30.00	30.00	27.80	NONE	0.11	1.16	1.29	1.27	0.0294	-3.9410
[illegible]	11.97	101.5	0.81	17.93	29.19	30.00	28.67	NONE	0.11	1.25	1.37	1.37	0.0306	-3.9103
[illegible]	12.13	92.6	-4.46	18.32	29.28	30.00	30.61	NONE	0.12	1.24	1.37	1.36	0.0451	-3.7349
[illegible]	12.54	77.7	-5.72	8.76	27.36	30.00	32.83	NONE	0.27	1.00	1.26	1.27	0.0765	-3.2995
[illegible]	12.[illegible]	47.6	-9.[illegible]	9.15	29.44	30.00	35.39	NONE	0.27	0.67	0.86	0.95	0.1244	-2.7015
[illegible]	12.[illegible]	10.0	-15.01	9.59	29.52	30.00	37.57	NONE	0.28	0.16	0.20	0.44	0.1838	-1.9654
[illegible]	12.[illegible]	-1[illegible]	-15.01	9.80	30.00	16.12	37.57	NONE	0.28	0.24	0.47	0.75	------	------
[illegible]	1[illegible]	-17.2	-14.[illegible]	10.55	30.00	17.92	39.19	NONE	0.25	0.23	0.35	0.60	------	------
[illegible]	13.66	-3[illegible]	-14.[illegible]	22.42	30.00	29.41	39.19	NONE	0.11	0.49	0.50	0.61	0.2396	-1.2772
[illegible]	14.[illegible]	-7[illegible]	-1[illegible].57	22.25	30.00	29.26	35.14	NONE	0.11	1.00	1.03	1.14	0.2843	-0.7260
[illegible]	14.20	-12[illegible].7	-19.57	26.04	30.00	30.00	31.34	NONE	0.09	1.41	1.42	1.51	0.3206	-0.2744
[illegible]	14.[illegible]	-144.3	-19.57	26.27	30.00	30.00	29.73	NONE	0.09	1.58	1.58	1.67	------	------

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STAR MANUFACTURING CO. 5600 S. I-35 OKLAHOMA CITY, OK. JOB SRLOFRA
[illegible] FILE TEST. TMP. 3
[illegible] MOMENT AND STRESS REPORT PAGE 22
NUMBER 4 - 5 LOAD CONDITION 4 - P=5.29 KIPS U.C.=1.67

POINT ID	AXIAL FORCE (KIP)	MOMENT (KIP-FT)	SHEAR FORCE (KIP)	-ALLOWABLE STRESS- FA (KSI)	FBO (KSI)	FBI (KSI)	ALLOW SHEAR (KIP)	A/H RATIO	-UNITY CHECK- UCA	BEND (OF)	BEND (IF)	MAX. COMB UC	DEFLECTIONS DELTA-X (IN)	DELTA-Y (IN)
4*	21.70	0.0	10.79	13.03	14.42	30.00	21.84	NONE	0.33	0.00	0.00	0.33	0.0000	0.0000
[illegible]	21.70	-12.[illegible]	10.79	15.60	30.00	23.31	26.77	NONE	0.26	0.43	0.48	0.74	0.1914	0.0070
[illegible]	21.70	-37.4	10.79	14.59	30.00	23.03	35.62	NONE	0.26	0.88	0.87	1.13	0.5051	0.0179
[illegible]	21.70	-[illegible]	10.79	13.60	30.00	22.75	41.69	NONE	0.26	1.10	1.05	1.30	0.6953	0.0233
[illegible]	21.70	-[illegible]	10.79	12.63	30.00	22.46	41.69	NONE	0.25	1.20	1.14	1.40	0.7567	0.0231
[illegible]	21.70	-1[illegible]	10.79	11.77	30.00	22.17	37.85	NONE	0.25	1.26	1.21	1.46	0.7052	0.0176
[illegible]	21.70	-13[illegible].2	10.79	11.02	30.00	21.87	32.95	NONE	0.25	1.28	1.24	1.50	0.5467	0.0074
[illegible]	21.70	-14[illegible].[illegible]	10.79	10.68	30.00	21.73	30.94	NONE	0.25	1.28	1.26	1.51	------	------

Figure B.3 Stress and Deflection Data, Full Live Load, Frame 2 Continued

APPENDIX C

TYPICAL TEST RESULTS

(Frame 7, Full Live Load, March 24, 1981)

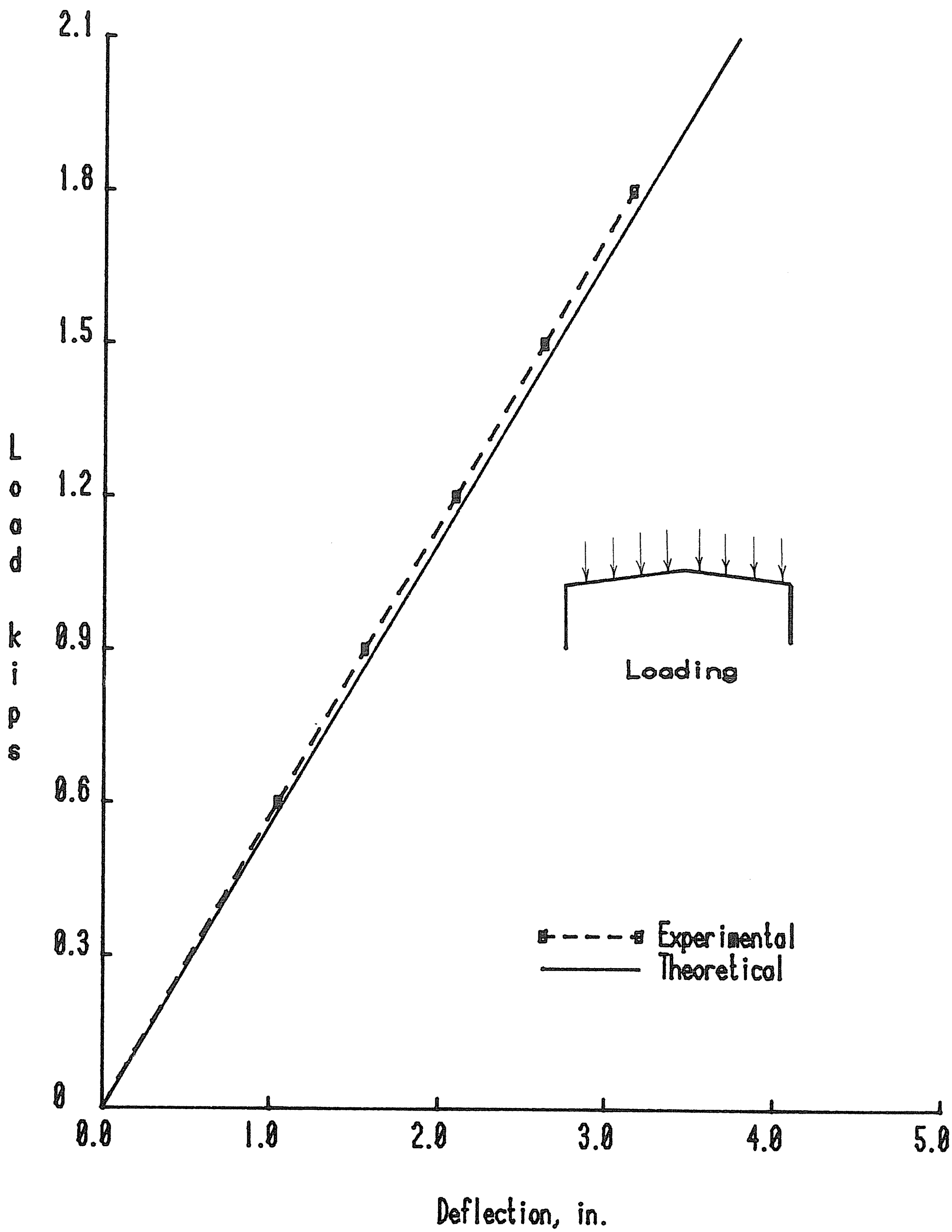

Figure C.1 Load vs. Centerline Vertical Deflection

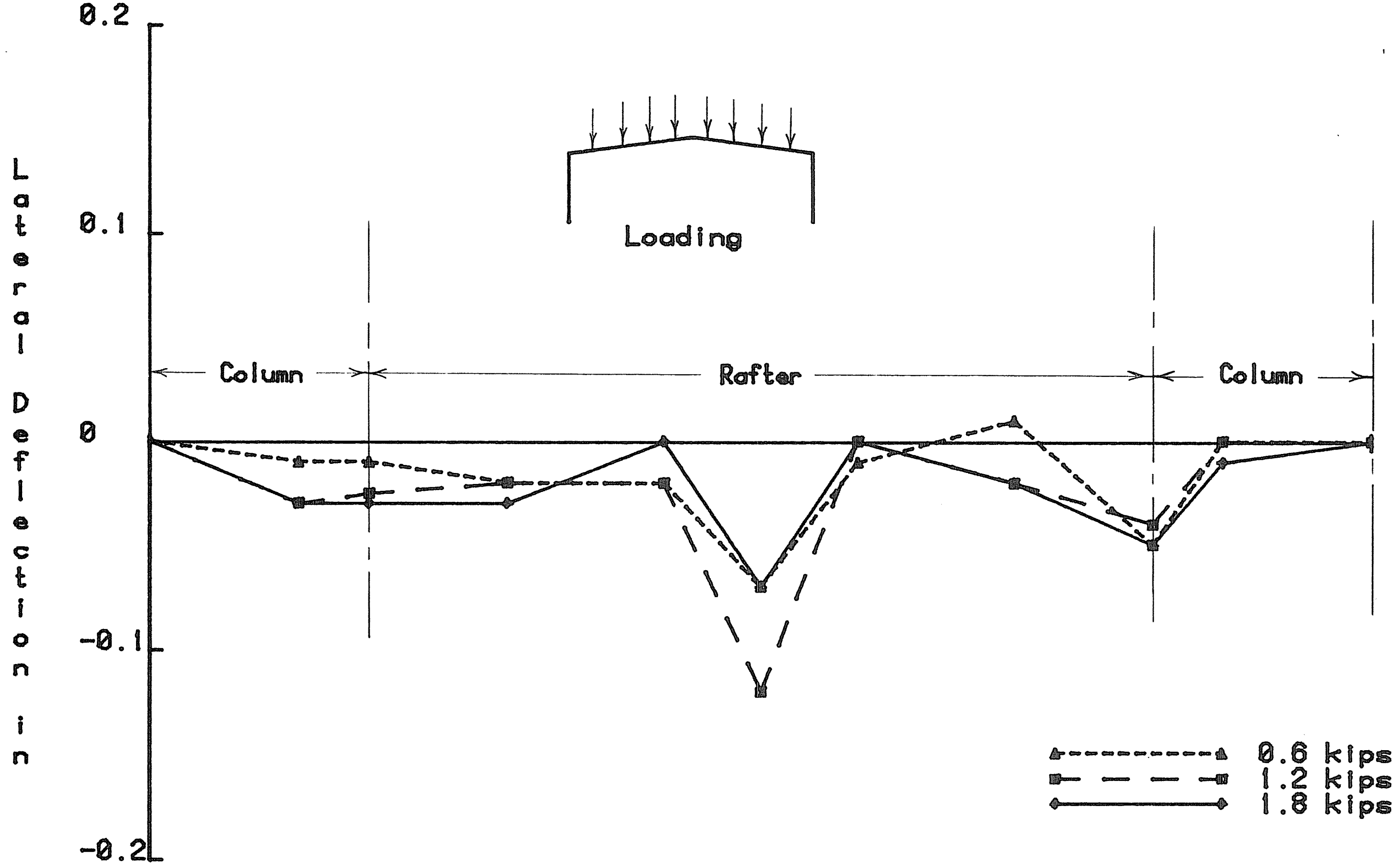

Figure C.2 Load vs. Lateral Deflection of Outside Flange, East Frame

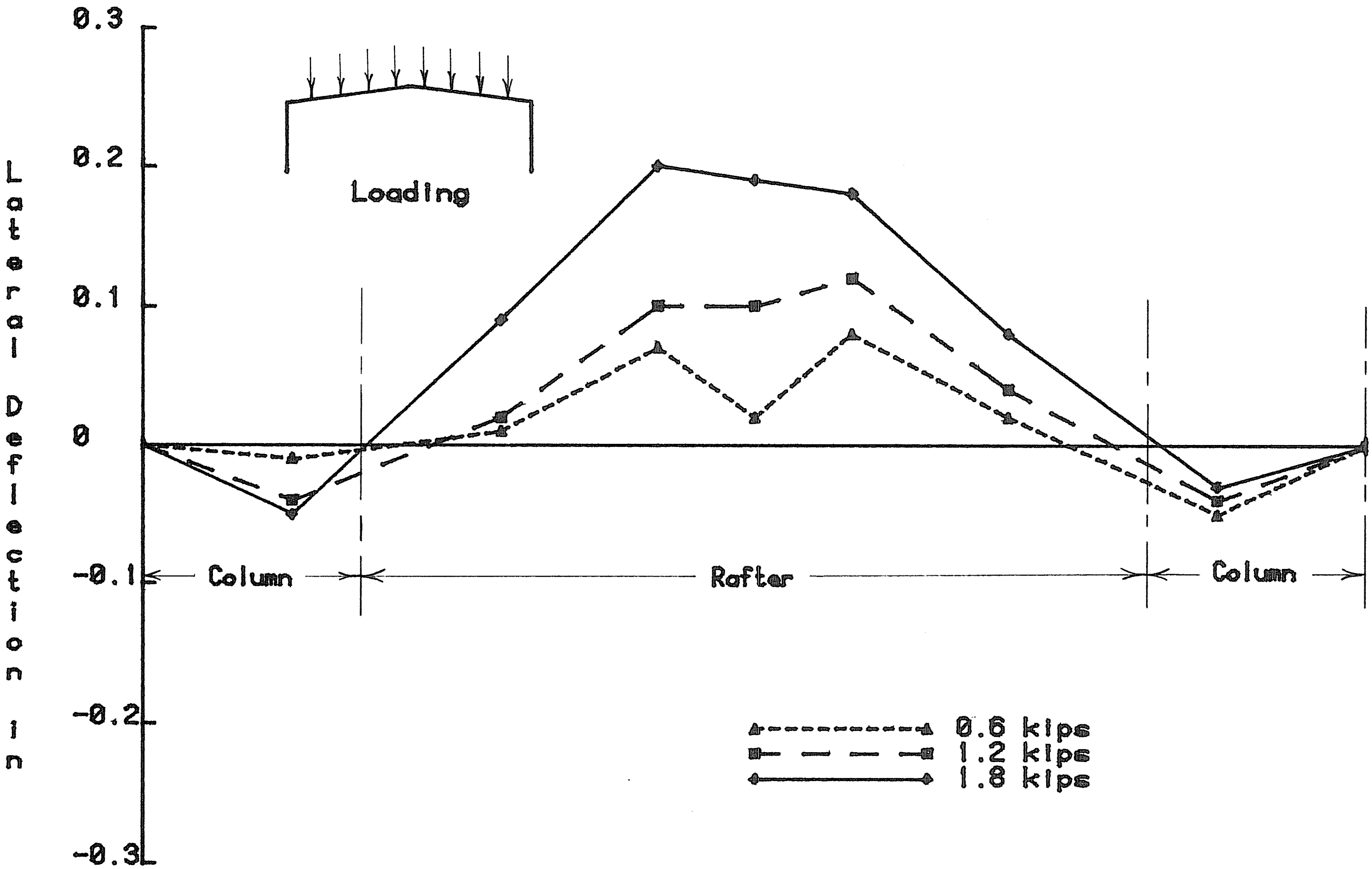

Figure C.3 Load vs. Lateral Deflection of Inside Flange, East Frame

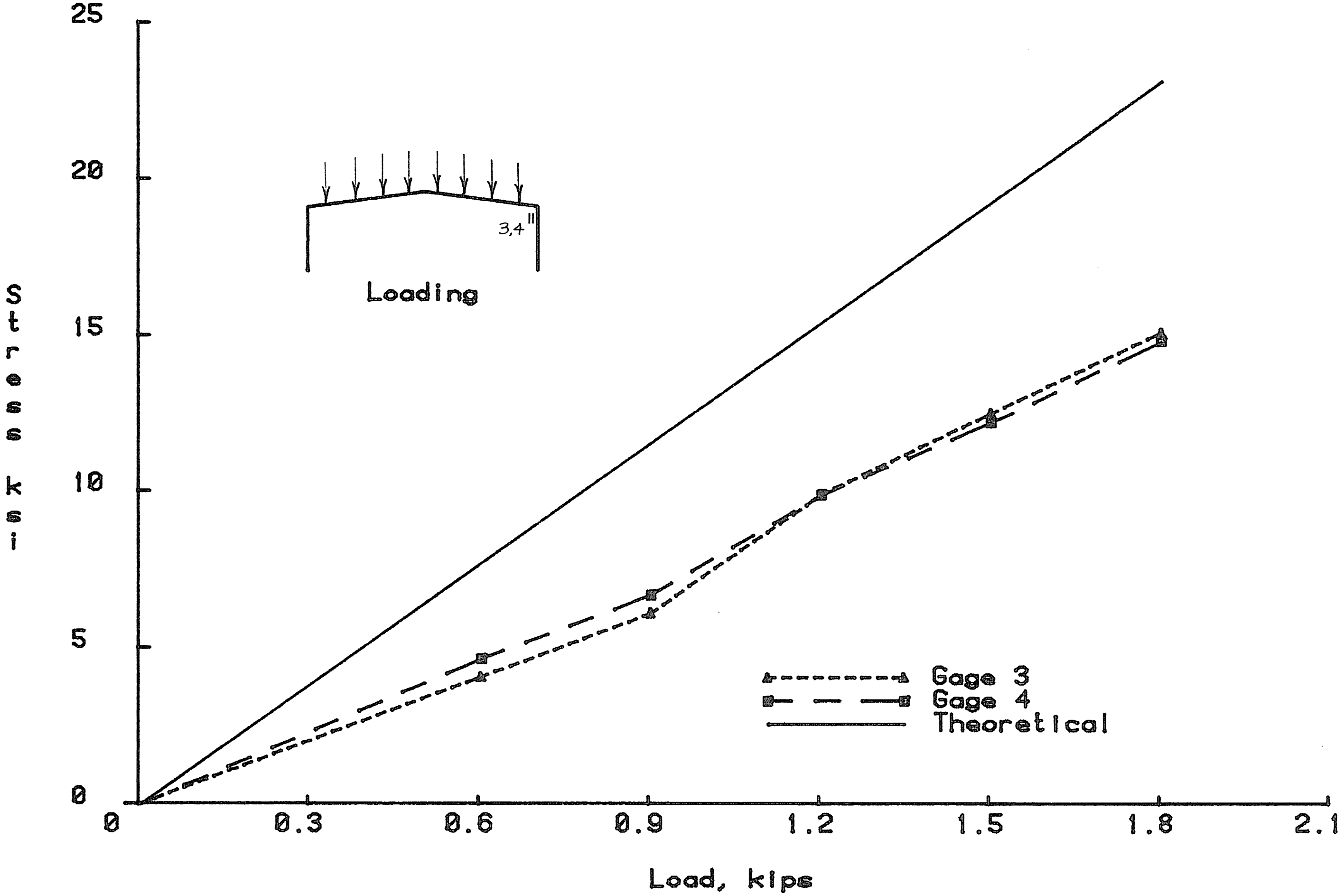

Figure C.4 Load vs. Stress, North Column at Knee

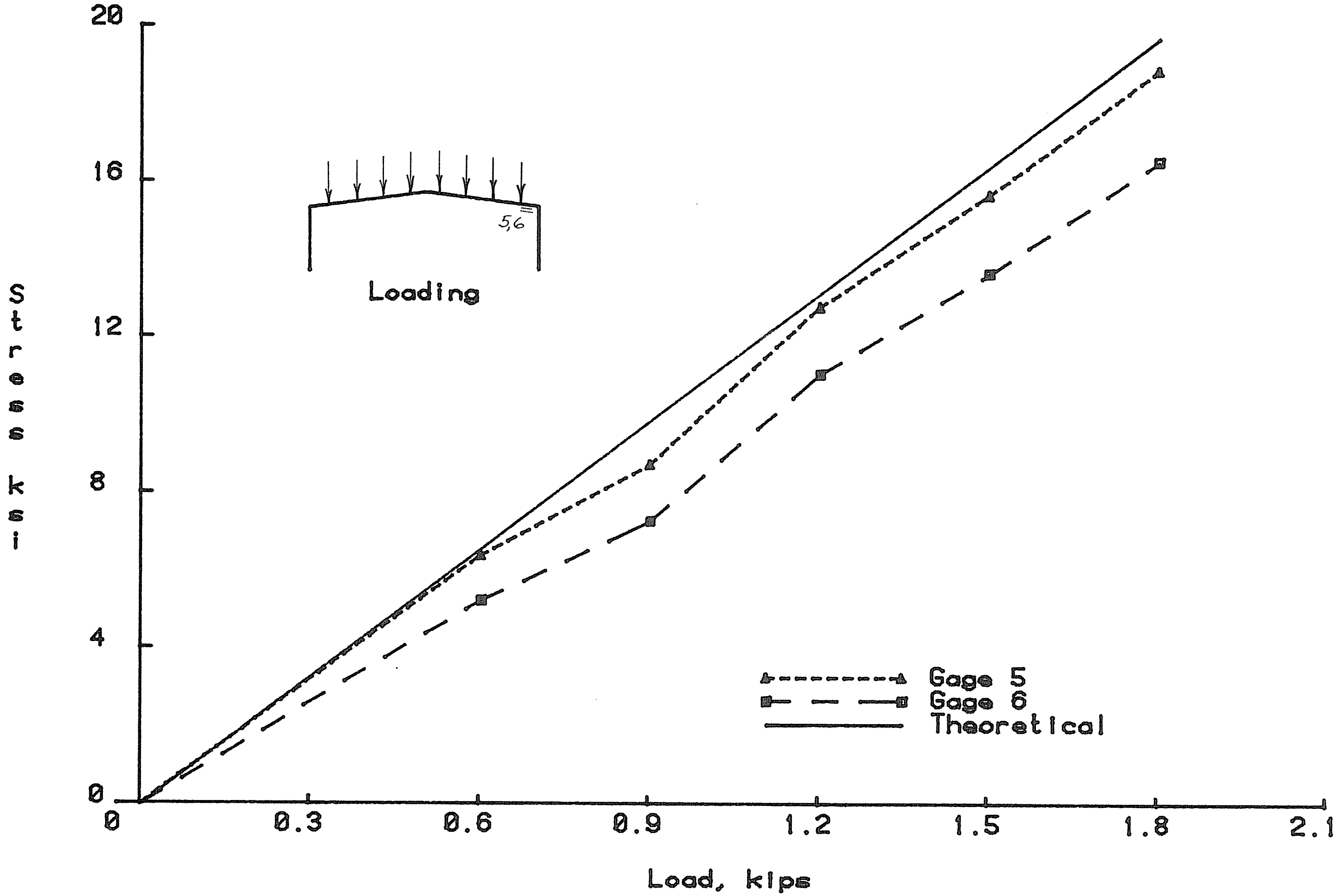

Figure C.5 Load vs. Stress, North Rafter at Knee

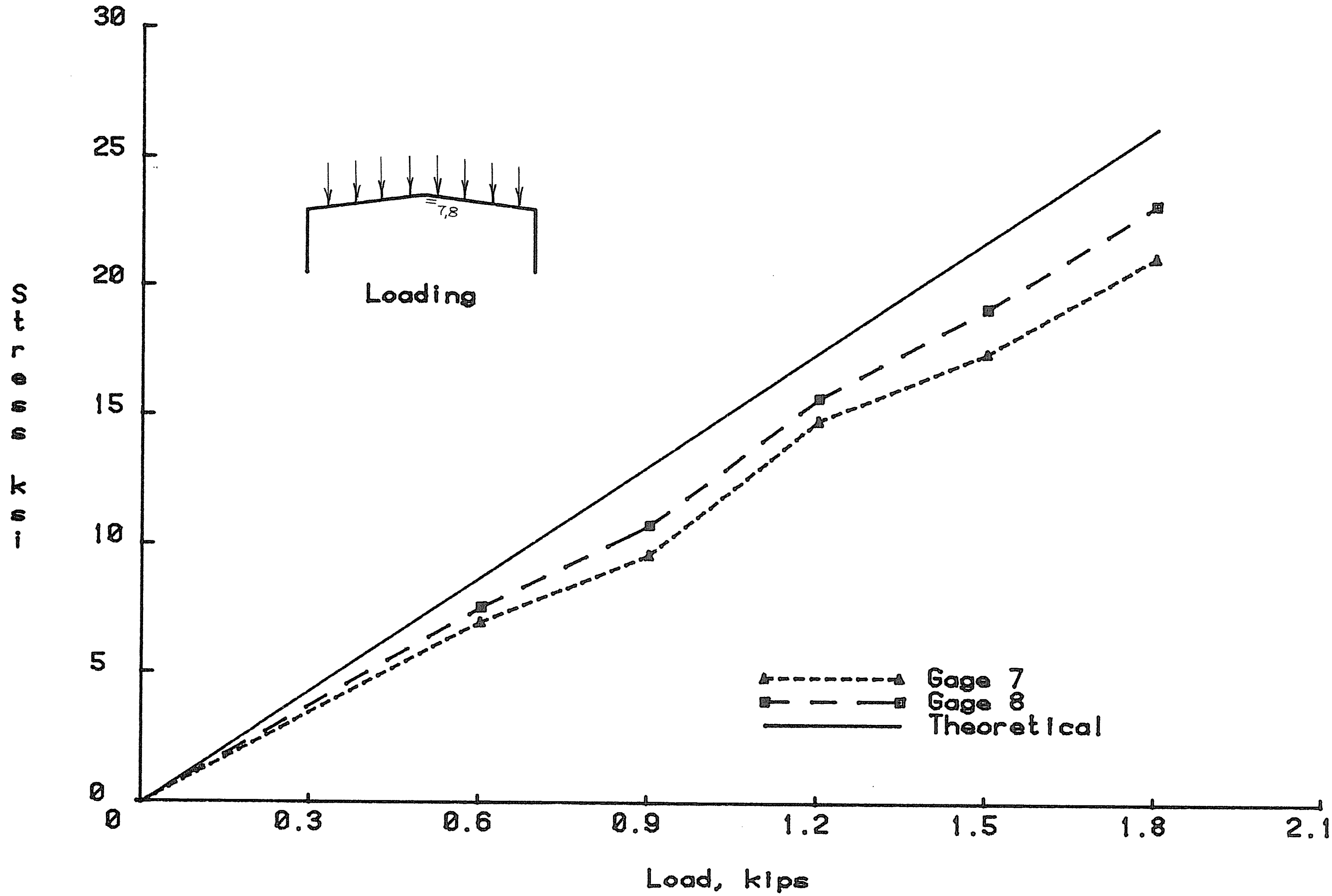

Figure C.6 Load vs. Stress, North Rafter at Peak

APPENDIX D

FINAL TEST

(Frame 8, Full Live Load, June 21, 1982)

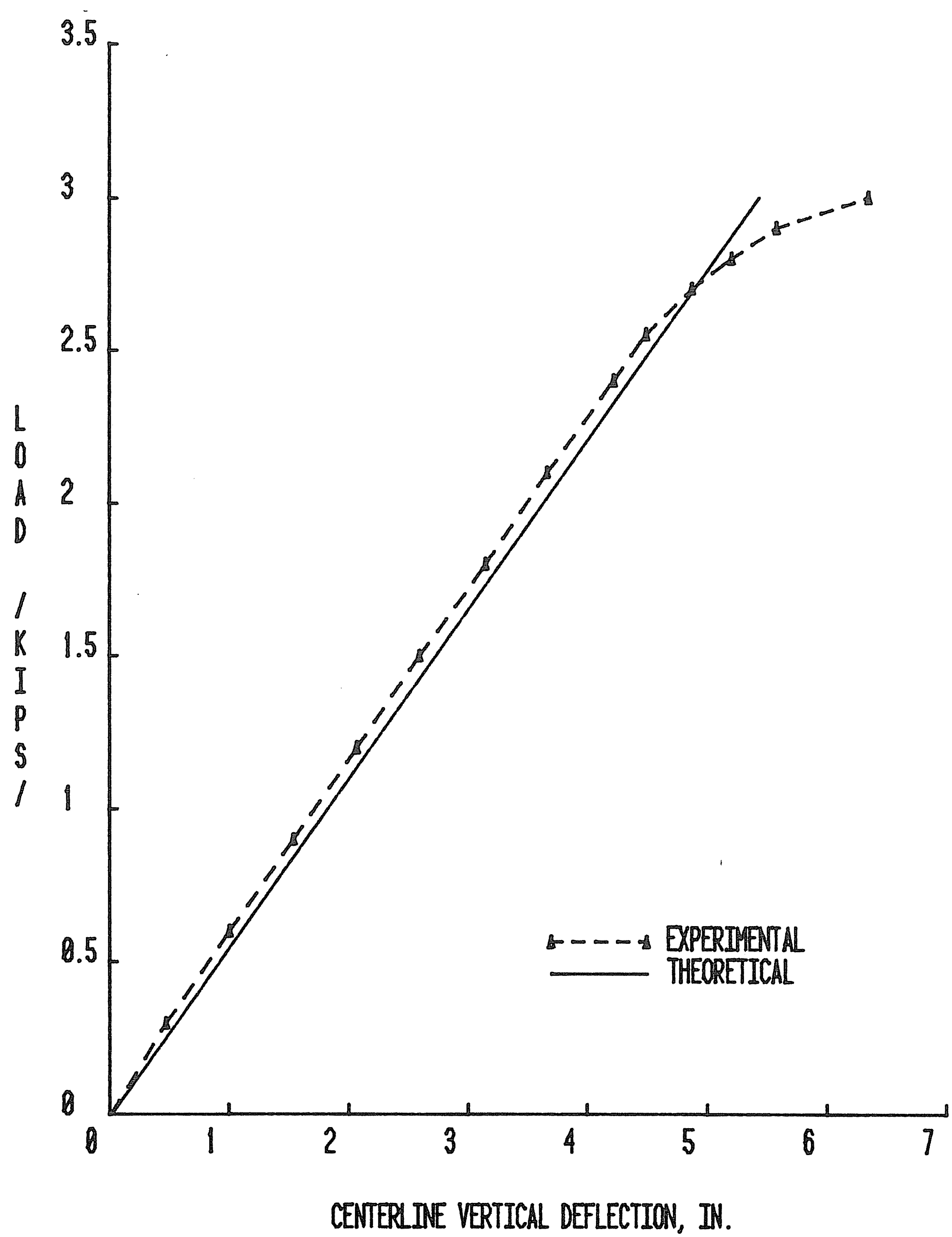

Figure D.1 Load vs. Centerline Vertical Deflection

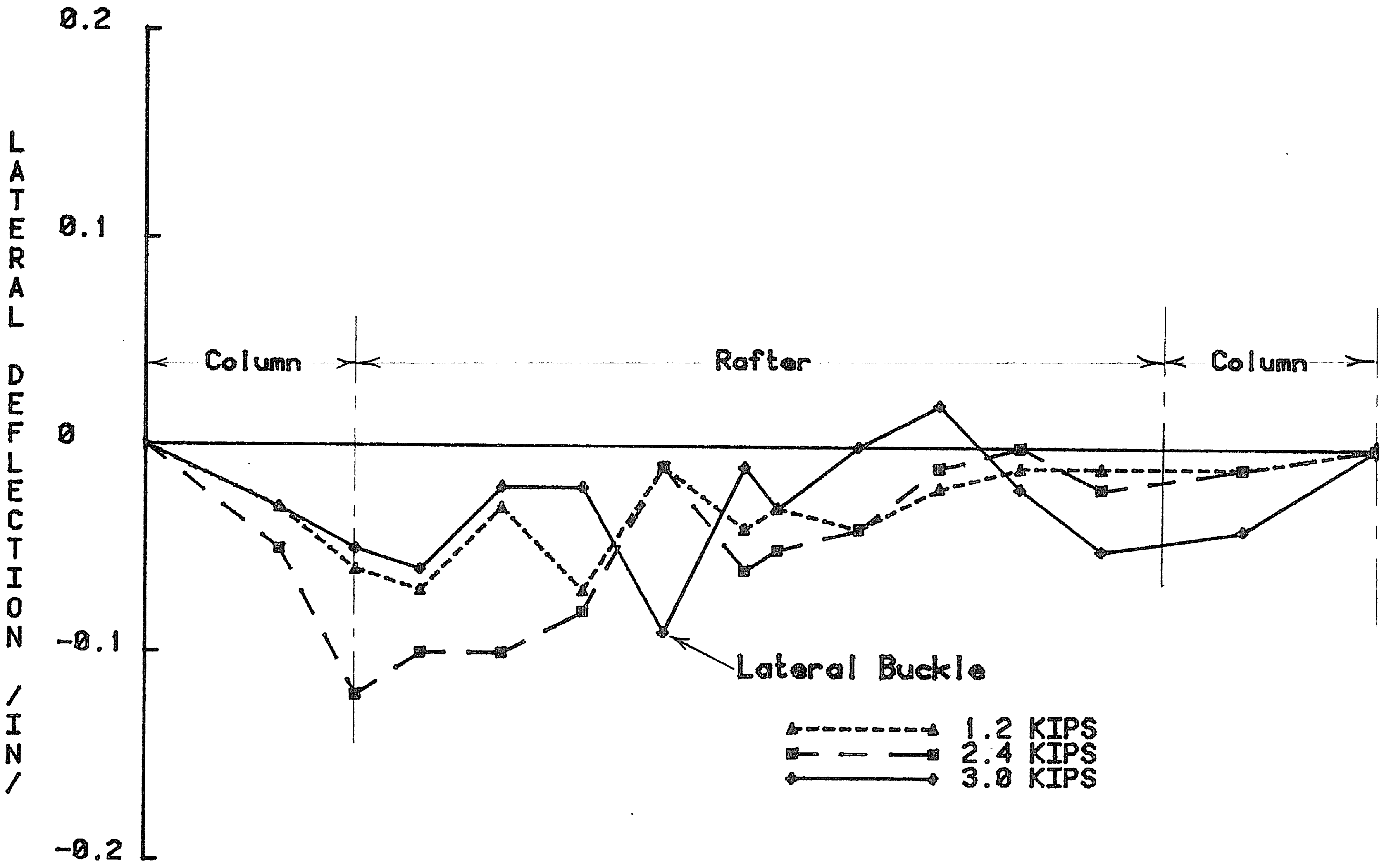

Figure D.2 Lateral Deflection of Outside Flange

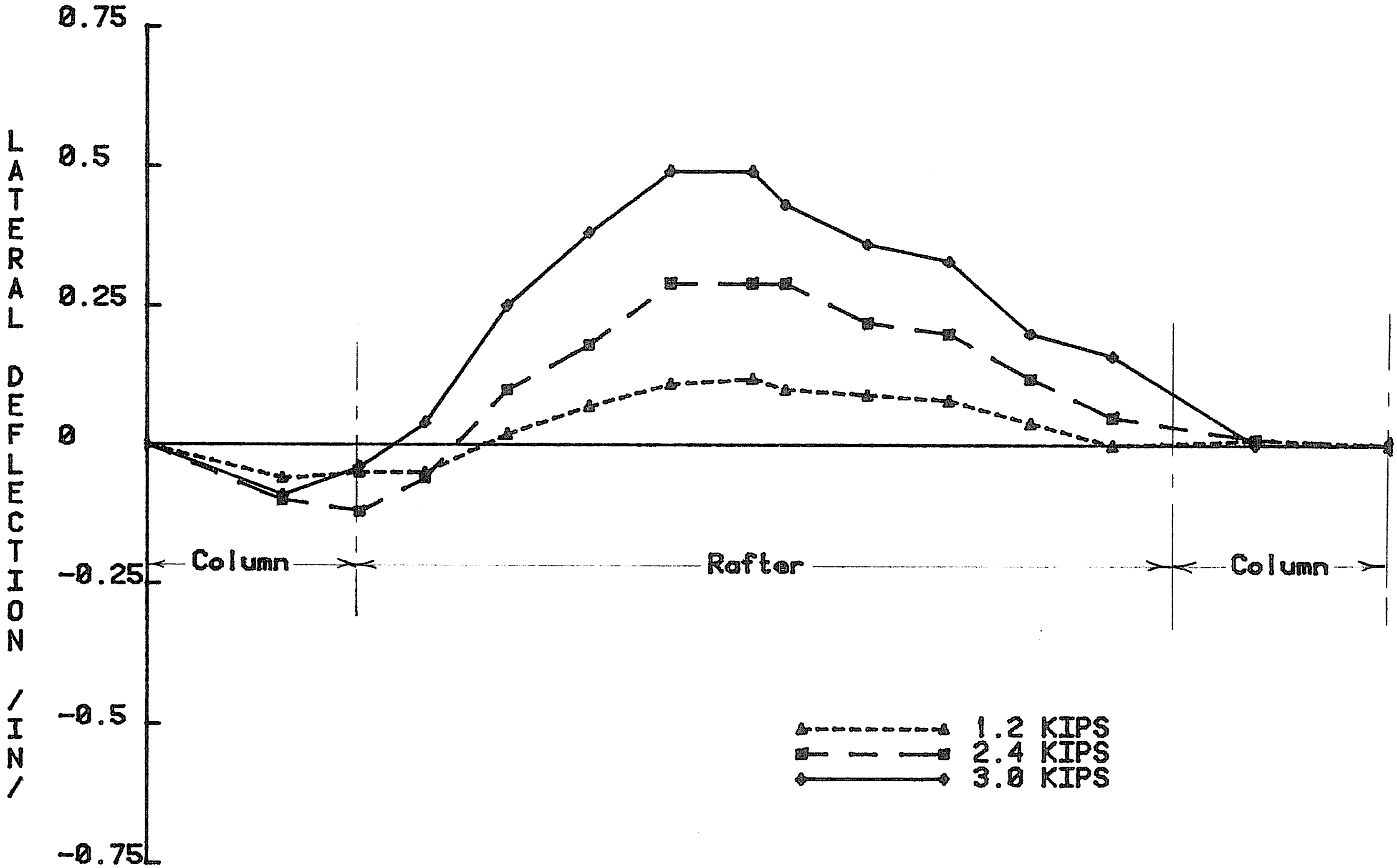

Figure D.3 Lateral Deflection of Inside Flange

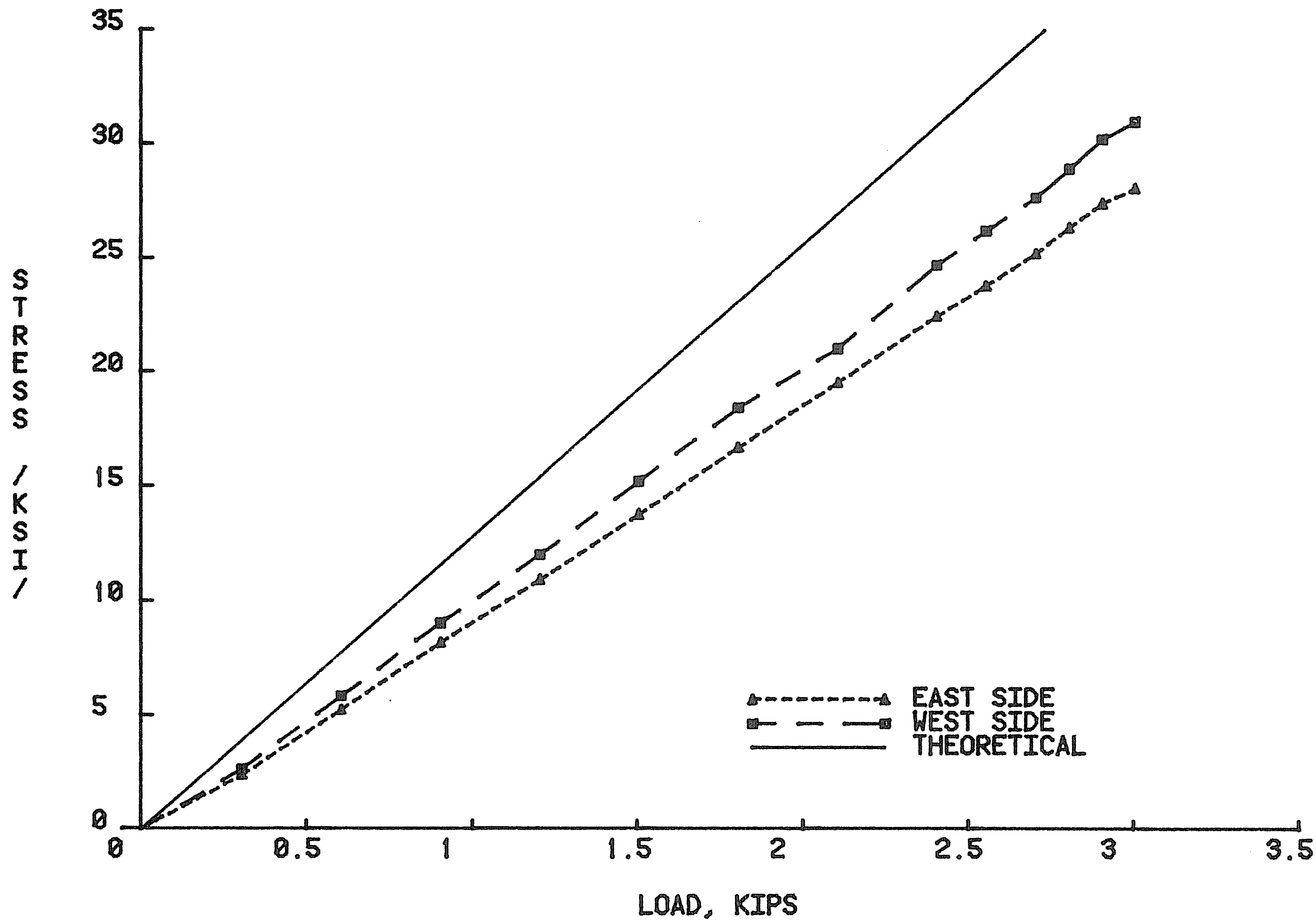

Figure D.4 Load vs. Stress in Column at Knee

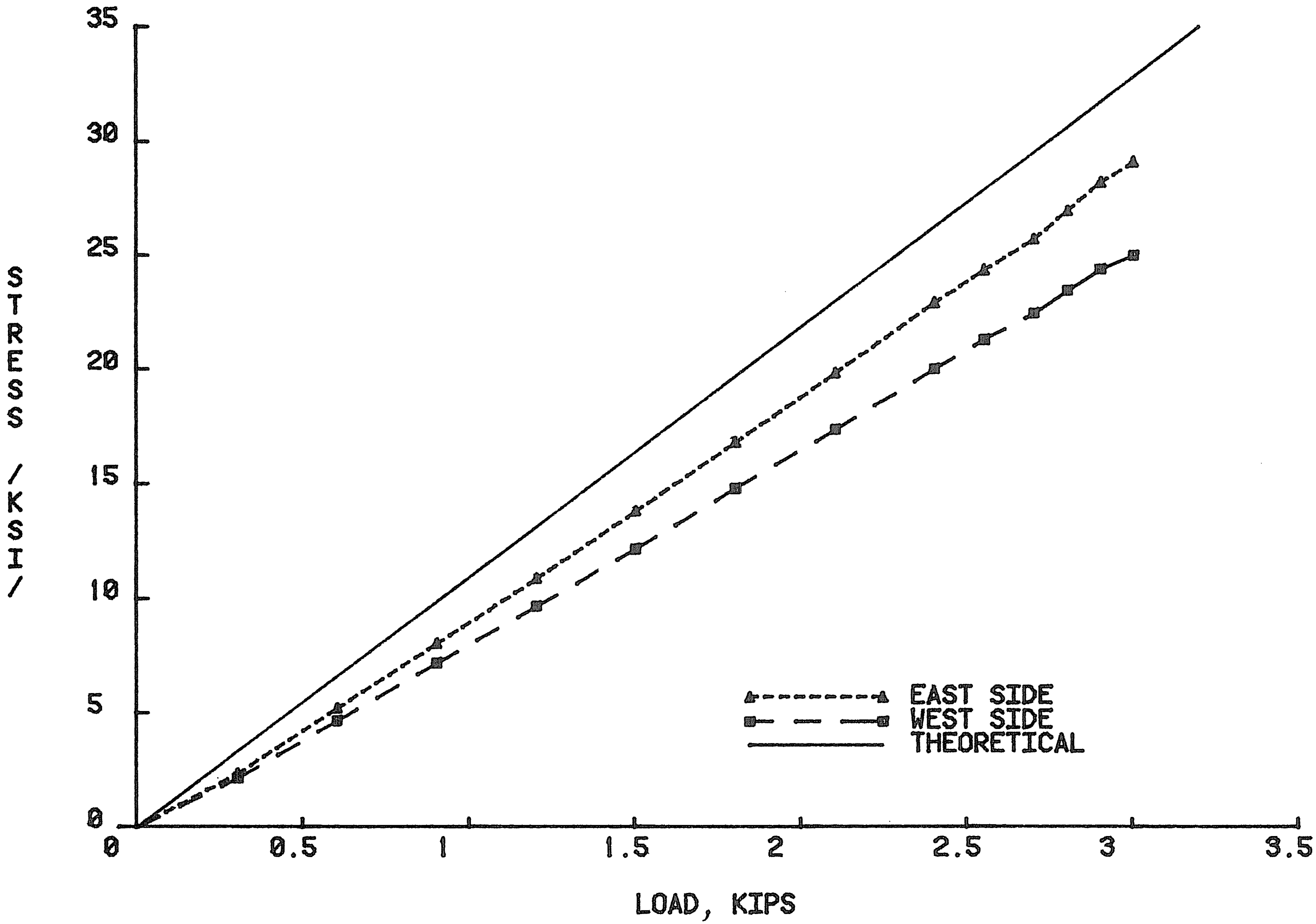

Figure D.5 Load vs. Stress in Rafter at Knee

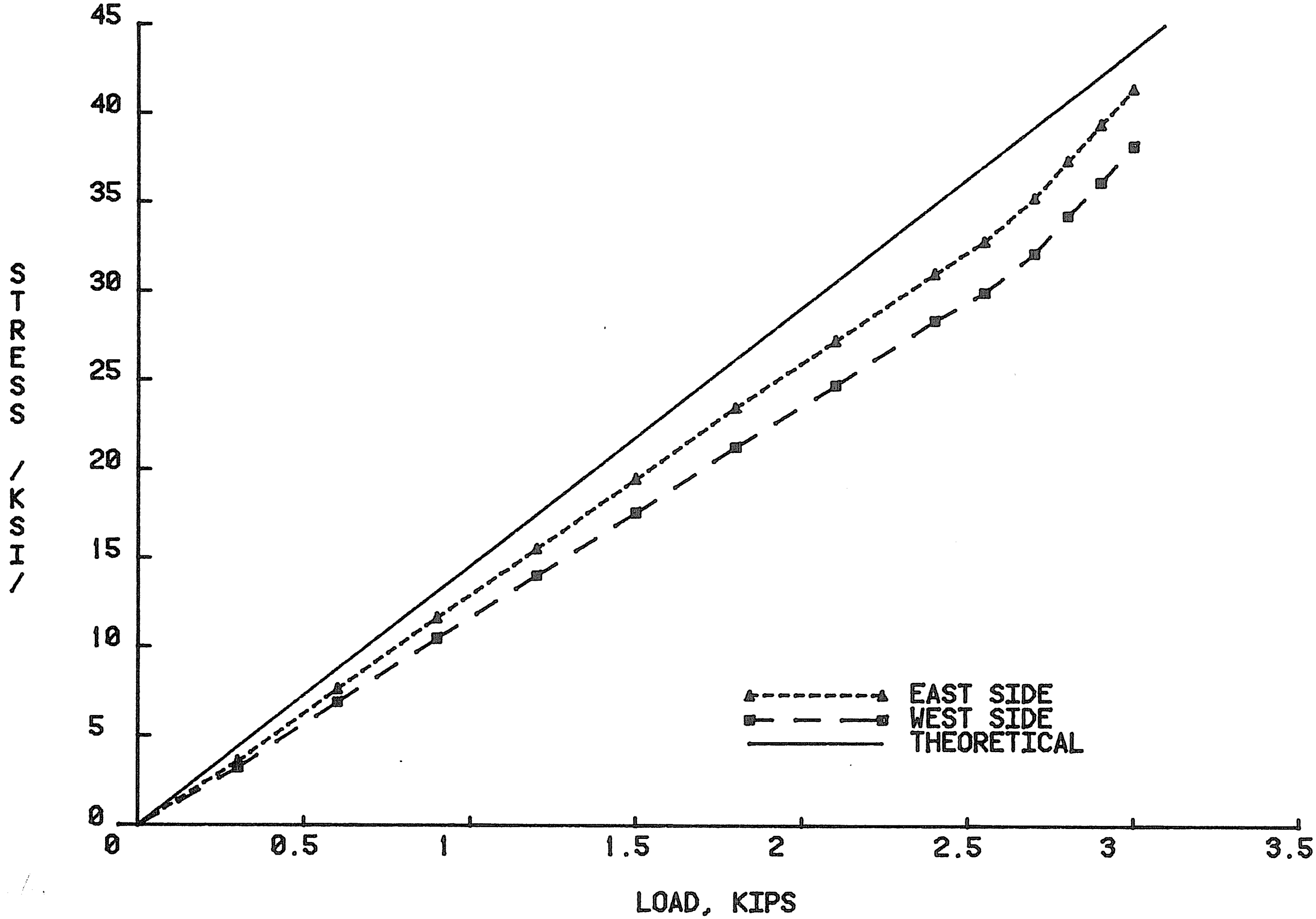

Figure D.6 Load vs. Stress in Rafter at Peak

APPENDIX E

TYPICAL ANALYSIS USING LEE PROCEDURES

FRAME 1 / Standard Bracing / Full Live Load = 5.13 k

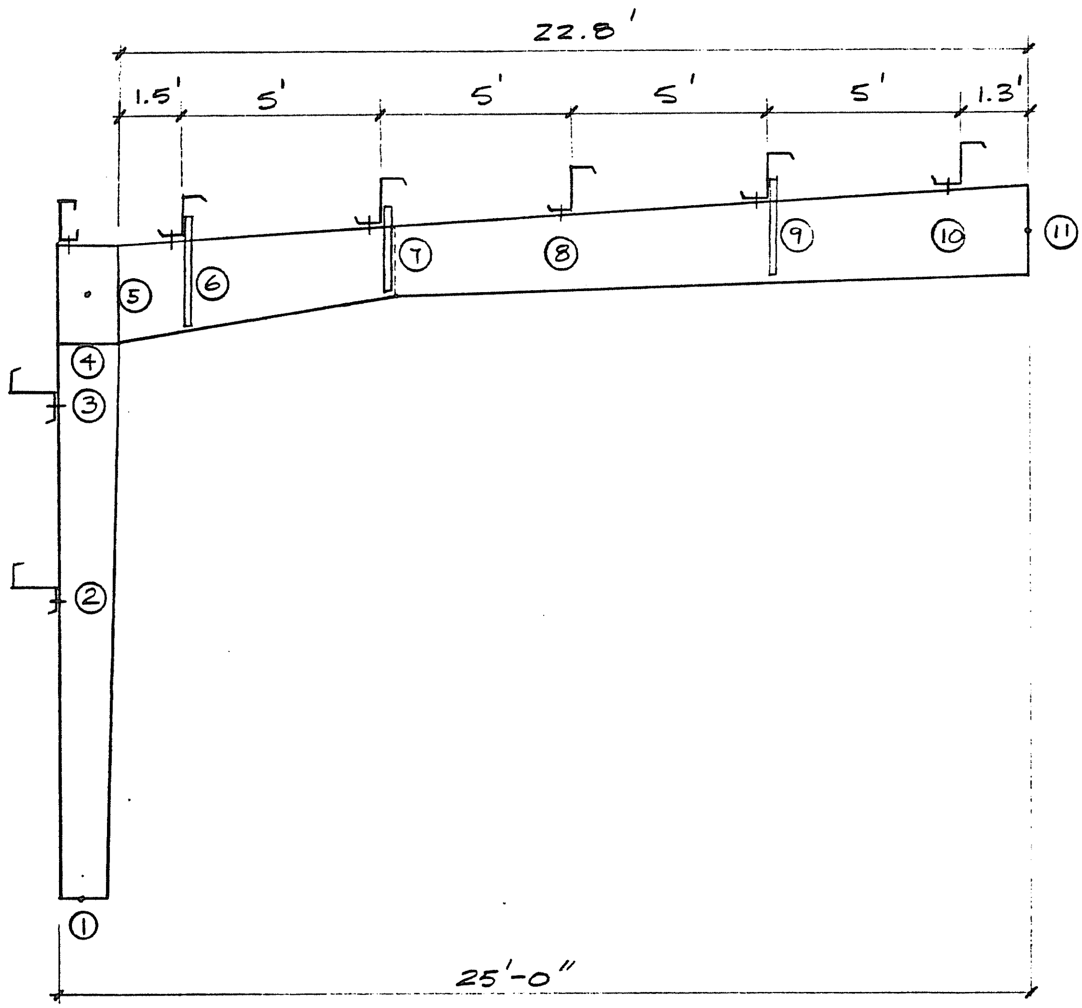

Table of Properties - Taken from Appendix B.

Property \ PT. No.	5	6	7	8	9
A, in^2	6.16	6.05	5.25	4.17	4.44
d, in.	20	19.4	15.15	15.43	17.42
I_x, in^4	359.7	335.1	188.2	161.1	212.2
I_y, in^4	5.21	5.21	5.21	4.48	4.48
S_x, in^3	36.0	34.5	24.8	22.6	26.3
r_T, in.	1.17	1.18	1.22	1.26	1.24
Moment, k-ft.	-142.5	-128.7	-35.1	31.8	77.4
Axial Load, Kips	14.01	14.01	13.44	12.42	12.20

*From Star Manufacturing Company analysis

Critical location will be in rafter near knee.

Axial Stress

Strong Axis

$L_x = 22.8'$ $\quad$ $\left.\begin{array}{l} G_B = 0.79 \\ G_T = 1.26 \end{array}\right\} K_x = 1.245$ $\quad$ – From Star's program

$$\left(\frac{KL}{r}\right)_x = \frac{1.245\,(22.8)(12)}{5.58} = 61.0.$$

Weak Axis

Sect. 5-6 : Strong axis controls by inspection.

Sect. 6-7 : $G_L = \dfrac{1.5\,(5.21)}{5\,(5.21)} = 0.3$

$$G_R = \frac{5\,(5.21)}{5\,(5.21)} = 1.0$$

From alignment chart, $K_y = 0.70$

$$\left(\frac{K\ell}{r}\right)_y = \frac{0.70\,(5)(12)}{0.93} = 45.2$$

Strong axis controls

$$F_a = \frac{\pi^2 E}{(K\ell/r)_x^2} = \frac{\pi^2 (29000)}{(61.0)^2} = 76.9 \text{ ksi}$$

$$(F_a)_{cr} = \left[1 - \frac{F_y}{4(F_a)}\right] F_Y = \left[1 - \frac{50}{4(76.9)}\right] 50 = 41.9 \text{ ksi}$$

$$(F_e')_x = \frac{\pi^2 E}{\left(\frac{K\ell}{r}\right)_x^2} = 76.9 \text{ ksi}$$

Bending Stress

Sect. 5-6

$G_L = 10.0$ (hinged at end 5)

$$G_R = \frac{5\,(5.21)}{1.5} = 3.33$$

$K_S = 0.93$, $K_W = 0.94$ (Appendix F of ref. 2)

$$\left(\frac{Ld}{A_f}\right)_6 = \frac{1.5(12)(19.4)}{5(0.25)} = 279$$

$$\left(\frac{L}{r_T}\right)_6 = \frac{1.5(12)}{1.18} = 15.3$$

$$\gamma = \frac{d_L}{d_o} - 1 = \frac{20}{19.4} - 1 = 0.031$$

$$h_s = 1.0 + 0.023\gamma\sqrt{\frac{Ld}{A_f}} = 1.012$$

$$h_w = 1.0 + 0.00385\gamma\sqrt{\frac{L}{r_T}} = 1.0$$

$$F_{s\gamma} = \frac{18,900}{h_s K_s\left(\frac{Ld}{A_f}\right)} = 72.0 \text{ ksi}$$

$$F_{w\gamma} = \frac{\pi^2 E}{(K_w h_w L/r_T)^2} = 1384 \text{ ksi}$$

$$(F_{b\gamma})_e = \sqrt{F_{s\gamma}^2 + F_{w\gamma}^2} = 1386 \text{ ksi}$$

$$F_{b\gamma} = \left[1 - \frac{50}{6(1386)}\right]50 = 49.7 \text{ ksi} \quad \text{(inelastic)}$$

<u>Sect. 6-7</u>

$G_L = 0.3$, $G_R = 1.0$

$K_s = 0.77$, $K_w = 0.74$ (Appendix F of ref. 2)

$$\left(\frac{Ld}{A_f}\right)_7 = \frac{5(12)(15.15)}{5(.25)} = 727$$

$$\left(\frac{L}{r_T}\right)_7 = \frac{5(12)}{1.22} = 49.2$$

$$\gamma = \frac{19.4}{15.15} - 1 = 0.28$$

$$h_s = 1.0 + 0.023(0.28)\sqrt{727} = 1.174$$

$$h_w = 1.0 + 0.00385(0.28)\sqrt{49.2} = 1.008$$

$$F_{s\gamma} = \frac{18,900}{1.174(.77)(727)} = 28.76$$

$$F_{w_y} = \frac{\pi^2(29{,}000)}{[0.74(1.008)(49.2)]^2} = 212.5$$

$$(F_{b_y})_e = \sqrt{28.76^2 + 212.5^2} = 214.4$$

$$F_{b_y} = \left[1.0 - \frac{50}{6(214.4)}\right]50 = 48.1 \text{ ksi} \quad \text{(inelastic)}$$

Combined Axial and Bending

Sect. 5-6

$$f_a = \frac{14.01}{6.16} = 2.27 \text{ ksi}$$

$$f_b = \frac{142.5(12)}{36.0} = 47.5 \text{ ksi}$$

$$C_m = 0.85$$

$$\frac{f_a}{(F_a)_{cr}} + \frac{C_m}{(1 - f_a/F'_e)} \frac{f_b}{(F_b)_y} \leq 1.0 \quad \text{(AISC eqn. 1.6.1a)}$$

$$\frac{2.27}{41.9} + \frac{0.85}{(1 - 2.27/76.9)} \frac{47.5}{49.7}$$

$$= 0.054 + 0.837 = 0.891$$

$$\frac{f_a}{F_y} + \frac{f_b}{(F_b)_y} \leq 1.0 \quad \text{(AISC eqn. 1.6.1b)}$$

$$\frac{2.27}{50} + \frac{47.5}{49.7} = 1.001$$

Sect. 6-7

$$f_a = \frac{13.44}{5.25} = 2.56 \text{ ksi}$$

$$f_b = \frac{128.7(12)}{34.5} = 44.77 \text{ ksi}$$

$$C_m = 0.85$$

$$\frac{f_a}{(F_a)_{cr}} + \frac{C_m f_b}{(1 - f_a/F'_e)(F_b)_\gamma}$$

$$= \frac{2.56}{41.9} + \frac{0.85(44.77)}{(1 - 2.56/76.9)\,48.1} = 0.879$$

$$\frac{f_a}{F_Y} + \frac{f_b}{F_{b\gamma}} = \frac{2.56}{50} + \frac{44.77}{48.1} = 0.982$$

Predicted Critical Load

Controlling section was the rafter section near the knee where the interaction equation (AISC 1.6.1b) gave a value of 1.001. Thus for this analysis the critical load is essentially the same as was determined through Star's computer design program ie. $P_u = 5.13^k$.